Published in final edited form as:

Lancet. 2010 March 27; 375(9720): 1110–1119. doi:10.1016/S0140-6736(10)60062-1.

Environmental health in China: challenges to achieving clean air and safe water

Junfeng (Jim) Zhang, PhD,

University of Medicine and Dentistry of New Jersey -School of Public Health, Piscataway, NJ, USA

Denise L. Mauzerall, PhD,

Princeton University Woodrow Wilson School of Public and International Affairs and Department of Civil and Environmental Engineering, Princeton, NJ, USA

Tong Zhu, PhD,

Peking University College of Environmental Sciences and Engineering, Beijing, China

Song Liang, PhD,

The Ohio State University College of Public Health

Majid Ezzati, PhD, and

Harvard University School of Public Health

Justin Remais, PhD*

Emory University Rollins School of Public Health

Abstract

The health effects of environmental risks, especially those of air and water pollution, remain a major source of morbidity and mortality in China. Biomass fuel and coal are routinely burned for cooking and heating in almost all rural and many urban households resulting in severe indoor air pollution that contributes greatly to the burden of disease. Many communities lack access to safe drinking water and sanitation, and thus the risk of waterborne disease in many regions remains high. At the same time, China is rapidly industrializing with associated increases in energy use and industrial waste. While economic growth resulting from industrialization has improved health and quality of life indicators in China, it has also increased the incidence of environmental disasters and the release of chemical toxins into the environment, with severe impacts on health. Air quality in China's cities is among the worst in the world and industrial water pollution has become a widespread health hazard. Moreover, emissions of climate-warming greenhouse gases from energy use are rapidly increasing. Global climate change will inevitably intensify China's environmental health problems, with potentially catastrophic outcomes from major shifts in

*Correspondence to: Dr. Justin V Remais, Department of Environmental and Occupational Health, Emory University; address: 1518 Clifton Road Room 270, Atlanta, Georgia, 30322; phone: 404-712-8908, fax: 404-727-8744; justin.remais@emory.edu.

Contributors

JR, JZ and DM conceptualized and coordinated the preparation of the manuscript. All authors participated in data analysis, discussion and writing of the article.

Conflict of interest statement

We declare that we have no conflict of interest.

temperature and precipitation. Facing the overlap of traditional, modern, and emerging environmental problems, China has committed substantial resources to environmental improvement. China has the opportunity to both address its national environmental health challenges and to assume a central role in the international effort to improve the global environment.

Introduction

Rapid economic growth in China — a 10-fold increase in GDP over the last 15 years — has pulled hundreds of millions out of poverty.¹ Yet the environmental impacts of economic growth are of increasing concern for China's citizens and policymakers, and the unaddressed health consequences at regional and global levels pose major policy challenges. Despite the well-established links between poor air and water quality and adverse health outcomes,² many Chinese cities have air pollution levels well above health-based standards,³ and China's top environmental regulator classifies more than half of its water resources as too polluted for human use.⁴ These and an array of other environmental risks lead to an estimated 2.4 million premature annual deaths in China from cardiopulmonary and gastrointestinal diseases, cancers and a range of other diseases and injuries.⁵ Meanwhile, increases in fossil fuel use in China's industry, transport, and residential sectors have resulted in a steep rise in the emissions of greenhouse gases that cause global climate change, which has broad consequences for public health.

Significant progress has been made reducing the burden of disease associated with traditional environmental exposures, such as diarrheal disease caused by contaminated drinking water and poor sanitation. China has made technological strides in improving environmental quality, developing the world's largest high-speed rail network providing clean, efficient transport, requiring stringent vehicle fuel efficiency requirements that exceed the US standards, and committing to an ambitious expansion of renewable energy sources to at least 15% of all electricity used in China by 2020. Indeed, aggregate national health outcomes in China have improved steadily over the past few decades, with life expectancy at birth increasing by 2.6 years for men and 3.0 years for women between 1990 and 2001 alone.⁶ However, diseases associated with environmental factors remain a major source of ill-health, especially among poorer populations in China; the significant health disparities between the poor and wealthy in China are in part driven by higher exposures to polluted air and water in poor households and communities.⁷

China's population is subject to both traditional and modern environmental risk factors. *Traditional* risks include poor sanitation and indoor air pollution from combustion of coal, wood and crop residue (solid fuels). *Modern* risks are those associated with industrialization and urbanization including outdoor air pollution and industrial waste. These risks co-exist with several *emerging* risk factors, including climate change and the international transport of air pollutants. Despite frequent reference to China's environmental risks in the literature and popular media, little attention has been paid to synthesizing these risks, and their potential policy solutions, across sectors, sources and populations. Indeed, a comprehensive analysis of environmental indicators and health outcomes in China is absent. In this paper,

we address this gap, reviewing Chinese environmental data and yearly health statistics published over the past 20 years. We describe the changing patterns of environmental risks, considering major sources of air (including greenhouse gas pollutants) and water pollution, and the associated health outcomes both within, and downwind of, China (Table 1). We discuss the progress and remaining challenges in addressing these environmental health issues, emphasizing policy initiatives key to reducing China's environmental health risks today, while ensuring a safer and healthier future environment.

A changing environmental risk landscape

China is at a stage of development where environmental risks are changing rapidly, shifting from traditional to modern sources. In many large Chinese cities, household coal use is poised to fall from its position as the leading source of indoor air pollution. However, new sources of pollution such as formaldehyde and other synthetic chemicals released from building materials are increasing and driving a rapid promulgation of indoor air quality standards.⁸ Yet many communities are still exposed to both traditional and modern risks, neither of which shows signs of abatement. For example, residents on the periphery of Shaoguan City in Guangdong Province remain reliant on the age-old and hazardous practice of burning wood and crop residue indoors for cooking and heating.²² Meanwhile, these same residents are surrounded by the effluent of modern heavy industry,²³ which has led to heavy metal exposures that are linked to neurotoxic effects in children and other adverse health outcomes.²⁴

Over the last three decades, this overlap of traditional and modern risks has been complicated further by the largest rural to urban migration of people in recorded history. From 1978 to 2007 the proportion of the population living in urban areas increased from 18% to 45%, an increase of nearly 422 million new urban dwellers.⁹ Of these, more than 140 million are highly mobile migrants who move from villages to cities seeking work.²⁵ With this migration comes complex trade-offs between environmental risks in rural and urban settings. For instance, migrants from rural areas leave behind unsafe water supplies that put them at risk of waterborne infectious diseases, but they are exposed to new risks, such as urban air pollution, exclusion from healthcare, poor housing conditions and related communicable diseases.^{25–26} In addition, with the rising health impacts of global climate change, environmental risks in China are no longer limited to local or national emissions, but now have a substantial international component. Moreover, there are many other emerging issues such as occupational exposures, land use change, electronic waste disposal and food safety that are neglected at the moment, but are expected to impose large, future health consequences. The lack of systematically collected data on these issues disallows a credible risk analysis, yet action on several fronts is well-motivated by experience and data both.

Air pollution

When hazardous chemical or biological agents are added to the indoor or outdoor air, health risks result. Indoor combustion of solid fuels in simple household stoves releases large quantities of pollutants, leading to concentrations of respirable particles and carbon

monoxide frequently more than 10 times higher than health-based standards.⁸ Likewise, fossil fuel combustion from the industrial, transportation, and residential sectors as well as burning of agricultural wastes, results in air quality in modern cities and surrounding regions that is among the worst in the world.

Indoor air pollution from biomass and coal fuels

In China, indoor air pollution from burning solid fuels is one of the largest environmental health risk factors, leading to an estimated 420,000 premature deaths per year.⁸ The major health outcomes associated with this environmental risk include COPD, acute lower respiratory infection (ALRI), and lung cancer.⁸ COPD is responsible for 1.3 million deaths annually in China, and solid fuel use increases COPD incidence more than three-fold.⁸ Likewise, solid fuel use is a major risk factor for ALRI, which kills young children and therefore contributes more lost life-years per death than diseases that affect older people. Indoor air pollution from solid fuel combustion results in a particularly high disease burden in China because a large number of people are exposed to consistent, high levels of pollutants over their lifetimes. More than half of China's population is still rural and almost all of this population still uses solid fuels. Many urban communities still rely heavily on coal, despite plans to eliminate the fuel for household use. Making matters worse, approximately 100 counties (out of a total of roughly 1500) in China possess natural deposits of coals that contain high levels of toxic elements such as arsenic and fluorine, the burning of which has been linked to symptoms of arsenicosis in nearly 300,000 people in Southwestern China and dental and skeletal fluorosis in more than 10 million people in Guizhou Province.⁸

Reducing exposure to coal smoke is a major public health objective, and can dramatically improve health. For instance, simply adding chimneys to stoves resulted in more than 50% reductions in lung cancer and COPD risk in Yunnan province.⁸ Yet even after considerable investment through the National Improved Stoves Program, improving indoor air quality remains an elusive goal in China.

Reducing indoor air pollution from solid fuels

Since the early 1980s, China's National Improved Stoves Program has introduced more than 180 million improved stoves, more than all other developing countries combined. Compared with traditional stoves, the improved stoves are intended to have higher combustion efficiencies and be coupled with chimneys for diverting pollutants outdoors, and thus generally lead to reduced indoor pollutant concentrations. However, the magnitude of pollutant concentration reduction varies substantially depending on the type of improved stove.⁸ The National Improved Stoves Program ended in the mid-1990s, and the situation appears to be getting worse as coal use in rural areas is rising, often burned in stoves without chimneys. Piped gas and liquefied petroleum gas offer some hope, but widespread use of these cleaner fuels in rural households is unlikely to occur soon because of cost and supply issues. Hence, policy and technical interventions to make burning solid fuels less polluting are still of prime public health importance.

Outdoor air pollution

Outdoor air pollution in China originates from a variety of sources including residential and industrial coal combustion, a burgeoning transport sector, chemical releases from industry, outdoor burning of agricultural waste, and dust from construction, roads and deserts. About 70% of electricity in China is generated by burning coal, most of which has high sulfur content. Burning sulfur-rich coal emits high concentrations of sulfur dioxide and particulate matter, contributing to the formation of acid rain and sulfurous smog, which once infamously plagued major industrial centers in the early 20th century. At the same time, the number of motor vehicles in Chinese cities is increasing very rapidly. Beijing, for example, is currently adding more than 1,000 vehicles per day to its streets; at the end of 2008, the city boasted 3.5 million vehicles. Emissions from these vehicles lead to the formation of photochemical smog containing respirable particles and ozone not only within the city but also in the surrounding regions. The ozone concentrations in major Chinese cities frequently exceed WHO air quality guidelines.²⁷ Annual mean concentrations of respirable particles in Chinese megacities like Beijing and Shanghai often approach or are above 100 $\mu\text{g m}^{-3}$, about twice as high as in Tokyo, nearly four times as high as in New York City, and four times the WHO guideline.²⁸

In 2000, outdoor air pollution led to approximately 470,000 premature deaths in China.^{12, 18} Exposure to outdoor air pollutants (mainly respirable particles, ozone, and nitrogen dioxide) has also been associated with lung cancer, cardio-respiratory diseases and possibly low birth weight.^{13–14} The economic cost of mortalities and morbidities resulting from outdoor air pollution in a typical Chinese city was estimated to be approximately 10% of that city's GDP in 2000 and, depending on future technology and policies, is predicted to range from 8%–16% by 2020.¹² Other health consequences are indirect: the outflow of pollution from urban to rural regions, for example, increases concentrations of ozone in agricultural areas and depresses crop yields, threatening China's food security.²⁹ Given that China is adding a coal-fired power plant every week, and burns more coal than the next seven largest consumers in the world combined, controlling outdoor air pollution is a top policy priority for China.

Reducing outdoor air pollution

China's efforts to reduce outdoor air pollution have focused on sulfur dioxide and dust from the energy and industrial sectors. China is now installing and operating sulfur scrubbers on most new power plants, and such efforts have decreased national emissions of sulfur dioxide and dust since 2005 even as energy production has continued to rise (Figure 1). Similarly, a national policy requiring leadless gasoline instituted in 2000 has reduced lead concentrations in urban air. However, media reports of industrial emissions of lead (mainly from lead smelter facilities in rural areas) have recently increased sharply, raising public awareness and concern. China's 11th Five Year Plan may aid in addressing major outdoor air pollution challenges by setting 2010 targets for reducing energy consumption per unit GDP by 20% and increasing renewable energy to 10% of total energy sources. However, given that ambient concentrations of air pollutants in most Chinese cities are currently several times higher than in typical Western cities, major long-term challenges remain for improving China's outdoor air quality.

International pollution transport

Observations and atmospheric models have clearly shown that air pollutants are transported between countries and continents.¹⁷ Satellite observations of dust transport across the Pacific show that emissions in Asia reach surface locations in the United States in 2–3 weeks. Circumpolar transport of pollution around the globe at northern mid-latitudes can carry air pollutants between Asia, North America and Europe in approximately a month. Thus, pollutants with lifetimes of a few weeks or more can affect air quality in downwind countries.^{17–18}

Emissions of inorganic mercury, which has an atmospheric residence time of about a year, are widely recognized to be transported globally.³⁰ Microorganisms convert inorganic mercury into methyl mercury, which accumulates up the aquatic food chain, leading to high mercury concentrations in fish at the top of the food chain (eg. tuna, swordfish) worldwide. Exposure to methyl mercury is known to impair neurological development, particularly in fetuses, infants and children, and can adversely impact a baby's growing brain and nervous system.¹⁶ As much as two-thirds of global emissions of inorganic mercury comes from coal combustion, with China responsible for about 28% of the global total (600 tons/year).³⁰ Consumption of contaminated fish is the major source of human exposure to mercury,¹⁶ and complex fish migration patterns mean that people who consume fish protein both near and far from emission sources can be exposed to dangerously elevated levels of mercury.

Greenhouse gas pollutants

China's remarkable economic growth has been largely driven by the combustion of fossil fuels that emit greenhouse gases, which accumulate in the atmosphere and lead to changes in the global climate. China's emissions of the primary greenhouse gas carbon dioxide have been increasing rapidly (Figure 2). Although per capita emissions in China are currently at the global average and each person in the US emits approximately four times as much, in 2006 China surpassed the US as the country emitting the most carbon dioxide (Figure 2). China and the US are together responsible for about 40% of global emissions, and thus binding commitments from the two nations were needed, but failed to emerge, in the December 2009 climate treaty talks in Copenhagen.

China is also a large emitter of methane, the second most important greenhouse gas, which is emitted from rice paddies, landfills, coal mining, leaking gas distribution systems and a variety of natural sources. In addition to being a direct greenhouse gas itself, methane is also a precursor for ozone and contributes to the rising global background concentration of surface ozone and associated premature mortalities.³² Similarly, China is responsible for approximately 30% of global black carbon emissions from contained combustion.³³ Sources of particular importance for climate and health include diesel engines and residential and small-scale industrial coal combustion, with future increases in diesel engines in a rapidly growing transport sector potentially increasing that fraction. Black carbon, a key component of soot, is a significant contributor to global warming and may lead to decreases in regional precipitation. Soot particles are a well-established health hazard, thus efforts in China to improve diesel engines (or move to alternative transport technologies) and residential stoves have clear benefits for health, regional weather and global climate. On the other hand,

sulfate particles, formed from sulfur dioxide released from coal combustion, cool the climate,²¹ and thus success in reducing sulfur dioxide emissions, although of direct benefit to health, will allow the warming effect of the long-lived gases to be felt more strongly.

Water pollution

Water scarcity, drinking water and sanitation

China's water resources are stretched thin, amounting to less than 2,156 m³ per capita per year, slightly greater than India's 1,720 m³, but only 1/5 of the USA per capita supply and less than 1/4 of the world average supply.³⁴ Making matters worse, China's water resources are grossly uneven (Figure 3). The heavily populated northern river basins, with 44% of China's population and 65% of its cultivated land, have less than 13% of the supply, just 757 m³ per capita per year, well below the level commonly defined as "water scarcity" (1,000 m³ per year).³⁴ Water shortages compel populations to draw on more contaminated sources, possibly explaining associations observed between water scarcity and health effects, like esophageal cancer.³⁵ As industrial, agricultural and municipal uses of water compete for an increasingly limited supply, pollution of these resources stands to exacerbate shortages.

A large fraction of lakes and major rivers in China are classified as severely polluted, with only half of China's 200 major rivers and less than one-quarter of China's 28 major lakes and reservoirs suitable for use as drinking water after treatment.⁴ Water pollution varies significantly across the country (Figure 3), governed by geographical differences in population, industrialization, and treatment capacity. Nationwide, more than 300 million people rely on hazardous drinking water sources, costing China (a conservatively, but crudely estimated) 2% of rural GDP from morbidity and mortality from diseases associated with microbial and industrial pollutants.³⁶

Water pollution is especially severe in rural China where, historically, few drinking water and sanitation services were in place and development lagged until the late 1980s and early 1990s, when China's Patriotic Health Campaign invested enormous resources in improving rural water and sanitation services. Yet even with recent gains, coverage remains low. A national survey in 2006 of more than 60,000 rural households from across China found that only about half had access to a centralized public water supply, the remainder relying on untreated hand pump, well, or surface water sources.³⁷ Meanwhile, nearly half of more than 7,000 water samples drawn from a variety of rural supplies were unsafe for drinking, many contaminated with untreated sewage.³⁷ While the immediate risk of fecal-oral transmitted diseases from these sources is high, exposure to microbial pollutants can also have chronic implications: for instance chronic exposure to microcystins, a toxin produced by cyanobacteria in nutrient polluted waters, leads to liver cancer.

To confront deteriorating rural water quality, major investments in basic sanitation services will be needed to interrupt transmission of water-related pathogens, some of which, like schistosome parasites, have re-emerged in regions that had previously achieved elimination.³⁸ Based on the most recent estimates of the Ministry of Health, rural coverage of improved sanitation in 2007 was just 57%, and the majority of wastes from both

improved and unimproved lavatories in these regions are returned to the environment untreated as fertilizer. Major investments are on the horizon: the government recently set the goal of 65% sanitation coverage in rural China by 2010.

Reducing waterborne infectious disease

Access to piped water increased from 30% of the population in 1985 to 77% in 2007 and, despite a massive increase in its urban population, the access among urban residents reached nearly 94% in 2007.^{9–10} Paralleling this and partly as a result of this improvement, there has been a reduction in water-related infectious diseases. Incidence of the six reportable water-related diseases in China's National Notifiable Infectious Disease Reporting system (hepatitis A, cholera, dysentery, typhoid/paratyphoid, other infectious diarrhea, and schistosomiasis) has declined steadily over the past two decades.¹⁰ In 2008, incidence of cholera, dysentery, typhoid and paratyphoid was 25 per 100,000 population, with 63 deaths reported, down from 319 per 100,000 and 2610 deaths in 1985 (Figure 4).¹⁰ While the reporting system is thought to underestimate actual incidence (underreporting for dysentery, for example, can range from 44 to 71 percent across the country),¹¹ these gains are impressive, and will likely be sustained with the Ministry of Health's plans to initiate a national water quality surveillance network.¹⁰

Chemical contamination of water resources

Relying on unprotected, untreated water sources puts residents at risk of chemical contamination from adjacent industries, which is widespread and severe in China. Recent epidemiological studies suggest that drinking water contaminants like nitrate/nitrite and chromium are a major risk factor for digestive system cancers (i.e., stomach cancer, liver cancer, esophageal cancer, and colorectal cancer). These cancers have the highest mortality rate among malignant neoplasms in China, 73 per 100,000 in 2005.¹⁰ Estimates attribute about 11 percent of digestive cancer cases to chemical contaminants in drinking water, indicating that the disease burden from industrial water pollution, from oil and gas industries, manufacturing and other sources, is already posing major challenges for the health of China's citizens.¹⁵

Growth in China's industrial contamination shows few signs of abatement. The past two decades have witnessed unregulated and increasing industrial discharges and excessive use of fertilizers and pesticides in agricultural areas. In northern China, water scarcity has exacerbated these emissions, forcing farmers to apply wastewater as irrigation to about 4 million hectares of agricultural land, resulting in contamination of food by heavy metals like mercury, cadmium, lead, copper, chromium, and arsenic, providing another route of exposure and shifting water pollutants to soil. Reliable data on industrial emissions are seldom made public, and national assessments of drinking water quality are rare – the last was conducted in 1988. When nationwide surveys are carried out, they often are limited in scope, focus solely on surface waters, and stop short of estimating risks to public health. Furthermore, study of the health risks of China's drinking water contaminants is hampered by the traditional challenges of environmental epidemiology, including long latency periods, poor exposure data, chemical mixtures and industry influence.^{36, 39} Improved monitoring, industry transparency, and new regulatory initiatives that could help to resolve these

difficulties are being catalyzed by citizen discontent with recent industrial accidents (see Panel 1), and would improve the base of evidence for future policy.

Reducing industrial water pollution

Recent progress limiting industrial water pollution includes large reported reductions (60–70% by mass) in annual emissions of arsenic and mercury to water,^{9, 40} as well as the construction of more than 60,000 industrial waste water treatment plants.⁴¹ Yet in the absence of monitoring and oversight, improvements to water quality from these efforts have not been documented. The water quality monitoring system in China is complex, where suppliers, public health, environmental and construction regulators each participate, but data are rarely made public and monitoring requirements often go unmet. A recent national survey in 2006 of several thousand suppliers revealed that more than a quarter of municipal plants and half of private plants were not properly monitoring the quality of the drinking water they provided.⁴² In response to the fragmentation of oversight, a pilot water quality surveillance network was established in 2007 covering five provinces and Beijing and Shanghai. The network was designed to comprehensively monitor drinking water quality at multiple points, including sources, distribution systems and point of use, along with human health status.¹⁰ The Ministry of Health intends to expand this program nationally, an ambitious plan which could rapidly improve the safety of China's drinking water resources.

Climate change vulnerability and water resources

China's significant vulnerability to climate change is, in part, experienced through an exacerbation of existing environmental risks and their health consequences. For instance, there is considerable evidence that climate change has, and will, lead to decreased precipitation in the already dry north and west of China, while depleting glacial water sources which supply much of China with water. Rainfall is already declining in northern China by about 20–40 mm/decade,³⁴ and projections indicate the uneven north/south precipitation distribution will intensify under future climate scenarios.⁴³ These projections indicate increased frequency of extreme precipitation in southern China, leading to flooding and accompanying loss of life such as the floods in 2007 that led to more than 1,200 deaths, loss of 12 million hectares of crops and one million houses.⁴³ These conditions are made worse when combined with increased temperatures, which promote the survival, replication and transmission of waterborne organisms including pathogens, algae and disease-carrying vectors. Algal blooms in lakes and reservoirs contaminate drinking water with toxic microcystins, leading to acute effects like skin rashes, diarrhea, and nerve and liver damage, and chronic outcomes including liver cancers.⁴⁴ These blooms are already a major threat, as was demonstrated recently when a bloom in Taihu Lake contaminated the water supply serving millions in Wuxi in Jiangsu province. Similarly, predicted changes in water resources threaten to exacerbate China's climate-sensitive infectious diseases carried by vectors and animal hosts, including malaria, Japanese encephalitis, dengue fever and schistosomiasis. While considerable uncertainty remains, projections of the distribution of these diseases include increases in dengue endemic areas and northward expansion of the climate-sensitive parasite *Schistosoma japonicum*.^{19–20}

Improving environmental health policies in China

A common view of the relationship between development and environment is that environmental conditions tend to initially worsen and then improve in later stages of economic development (as measured by income growth), a phenomenon referred to as the environmental Kuznets curve. Yet analytical and empirical evidence demonstrate that both the initial worsening and subsequent improvement of environmental quality are not inevitable consequences of development but, rather, highly affected by technology and policy choices.⁴⁵ In China, such choices have been closely linked to the heavy emphasis on economic growth as the single most important policy objective. To improve environmental health outcomes in China, there is need for risk management activities that cross sectors and agencies, with a special emphasis on social and environmental inequities.

China has successfully reduced extreme poverty through economic growth but, until very recently, has overlooked the widening inequalities in income, health, and access to clean water, sanitation and cleaner fuels.⁷ Thus despite growth in aggregate national income, the traditional environmental risk factors described earlier continue to severely affect the health of poor and marginalized communities.⁷ Each unit of intervention that reaches a poor household is likely to have a larger impact than if it reaches an affluent household,⁴⁶ and thus programs that disproportionately benefit the poor are called for, such as subsidies for high quality stoves and investment in rural water and sanitation services.

China has demonstrated an extraordinary ability to reduce emissions of pollutants when the reductions have high policy priority, such as the substantial cut in air pollutant emissions in the Beijing metropolitan region during the 2008 summer Olympics (see Panel 2). This success shows that policy formulation and implementation can and must overcome the complex interactions between central, provincial, and local governments, some of which take on the dual role of environmental regulator and source of poor environmental conditions. For example, energy policies targeted primarily towards industrial productivity may be partly responsible for limiting access to clean fuels among low-income rural households and for increases in some urban air pollutants. Similarly, factories and enterprises owned by local governments may be the largest polluters in some areas. A greater emphasis on regulatory enforcement is needed (including substantial fines and criminal penalties), and systems to objectively evaluate the success of specific regulatory actions must be instituted. China's recently released first National Environment and Health Action Plan⁴⁷ emphasizes the need to coordinate activities across multiple sectors and ministries. It identifies coordinated and shared data collection and environmental monitoring as a crucial feature of future environmental health policies.

Finally, past policies with demonstrated success in reducing environmental risks should form the basis for reform. Examples such as Hong Kong's 1990 low-sulfur fuel law, which led to an estimated increase in life expectancy of 20 days for women and 41 days for men,⁴⁸ and Beijing Olympic air quality policies, provide strong, direct evidence that improvements in environmental quality have immediate and long-term health benefits. China has acknowledged the need to improve its environmental record, shifting its development strategy from economic development to environmental sustainability in its 11th Five Year

Plan, and reiterating in Copenhagen its intention to reduce greenhouse gas emissions per unit GDP regardless of the actions of other countries. These environmental goals will have the most significant effect if achieved alongside a firm commitment from the Chinese government to formulate, implement and enforce effective environmental health policies.

Acknowledgments

The authors thank The China Medical Board for facilitating development of the manuscript, and five anonymous referees whose comments greatly improved the article. JZ is in part supported by an NIEHS Center Grant (#P30ES 05022) awarded to UMDNJ and Rutgers University. DLM is supported by Princeton University. TZ is in part supported by a grant from the Chinese Natural Science Foundation (20637020). SL is in part supported by an NIH/NIAID grant (R01 AI068854) to UC Berkeley. JR is supported by the NIH/NSF Ecology of Infectious Disease Program (grant 0622743) and Emory University's Global Health Institute. The views expressed in this article are solely those of the authors, and may not reflect the policies or views of the funding agencies.

References

1. World Bank. From poor areas to poor people: China's evolving poverty reduction agenda. Washington, DC: World Bank; 2009.
2. Prüss-Ustün, A.; Corvalán, C. Preventing disease through healthy environments. Geneva: World Health Organization; 2006.
3. HEI. Health Effects of Outdoor Air Pollution in Developing Countries of Asia. Boston, MA: Health Effects Institute; 2004. Report No.: Special Report 15.
4. MEP. Bulletin of China's Environmental Conditions. Beijing: Ministry of Environmental Protection; 2009.
5. WHO. China country profile. Geneva: World Health Organization; 2009. Quantification of the disease burden attributable to environmental risk factors.
6. Lopez, A.; Mathers, C.; Ezzati, M.; Murray, C.; Jamison, D. Global burden of disease and risk factors. New York: Oxford University Press; 2006.
7. Tang S, Meng Q, Chen L, Bekedam H, Evans T, Whitehead M. Tackling the challenges to health equity in China. *Lancet*. 2008 Oct 25; 372(9648):1493–1501. [PubMed: 18930531]
8. Zhang J, Smith KR. Household air pollution from coal and biomass fuels in china: measurements, health impacts, and interventions. *Environ Health Perspect*. 2007 Jun; 115(6):848–855. [PubMed: 17589590]
9. NBSC. China Statistical Yearbook. Beijing: National Bureau of Statistics of China; 2008.
10. MoH. 2007 Health Yearbook. Beijing: Ministry of Health; 2007.
11. Wang XY, Tao FB, Xiao DL, Lee H, Deen J, Gong J, et al. Trend and disease burden of bacillary dysentery in China (1991–2000). *Bulletin of the World Health Organization*. 2006 Jul; 84(7):561–568. [PubMed: 16878230]
12. Wang X, Mauzerall DL. Evaluating Impacts of Air Pollution in China on Public Health: Implications for Future Air Pollution and Energy Policies. *Atmospheric Environment*. 2006; 40(9): 1706–1721.
13. Pope CA III, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, et al. Lung Cancer, Cardiopulmonary Mortality and Long-Term Exposure to Fine Particulate Air Pollution. *J Amer Med Assoc*. 2002; 287(9):1132–1141.
14. Dockery DW, Pope CA III, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six U.S. cities. *The New England Journal of Medicine*. 1993; 329(24):1753–1759. [PubMed: 8179653]
15. WHO-UNDP. Environment and People's Health in China. Geneva: WHO; 2001.
16. NAS. Toxicological Effects of Methylmercury. Washington D.C: National Academy of Sciences, The National Academies Press; 2000.
17. Liu J, Mauzerall DL, Horowitz LW. Evaluating Inter-continental transport of fine aerosols : (2) Global Health Impacts. *Atmospheric Environment*. 2009b

18. Saikawa E, Naik V, Horowitz LW, Liu JF, Mauzerall DL. Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality, premature mortality and, radiative forcing. *Atmospheric Environment*. 2009 Jun; 43(17):2814–2822.
19. Zhou XN, Yang GJ, Yang K, Wang XH, Hong QB, Sun LP, et al. Potential impact of climate change on schistosomiasis transmission in China. *Am J Trop Med Hyg*. 2008 Feb; 78(2):188–194. [PubMed: 18256410]
20. Campbell-Lendrum D, Corvalan C. Climate change and developing-country cities: implications for environmental health and equity. *J Urban Health*. 2007 May; 84(3 Suppl):i109–i117. [PubMed: 17393341]
21. IPCC. Geneva, Switzerland: 2008. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
22. Liu S, Zhou Y, Wang X, Wang D, Lu J, Zheng J, et al. Biomass fuels are the probable risk factor for chronic obstructive pulmonary disease in rural South China. *Thorax*. 2007 Oct; 62(10):889–897. [PubMed: 17483137]
23. Zhuang P, Zou B, Li NY, Li ZA. Heavy metal contamination in soils and food crops around Dabaoshan mine in Guangdong, China: implication for human health. *Environ Geochem Health*. 2009 Feb 13.
24. Bao QS, Lu CY, Song H, Wang M, Ling W, Chen WQ, et al. Behavioural development of school-aged children who live around a multi-metal sulphide mine in Guangdong province, China: a cross-sectional study. *BMC Public Health*. 2009; 9:217. [PubMed: 19573251]
25. Hu X, Cook S, Salazar MA. Internal migration and health in China. *Lancet*. 2008 Nov 15; 372(9651):1717–1719. [PubMed: 18930533]
26. Jia ZW, Jia XW, Liu YX, Dye C, Chen F, Chen CS, et al. Spatial analysis of tuberculosis cases in migrants and permanent residents, Beijing, 2000–2006. *Emerg Infect Dis*. 2008 Sep; 14(9):1413–1419. [PubMed: 18760008]
27. Shao M, Tang XY, Zhang YH, Li WJ. Air and surface water pollution of city clusters in China: current situation and challenges. *Frontiers in Ecology and the Environment*. 2006; 7(4):353–361.
28. Parrish DD, Zhu T. Climate change. Clean air for megacities. *Science*. 2009 Oct 30; 326(5953):674–675. [PubMed: 19900921]
29. Wang XP, Mauzerall DL. Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment*. 2004 Aug; 38(26):4383–4402.
30. Pacyna EG, Pacyna JM, Steenhuisen F, Wilson S. Global anthropogenic mercury emission inventory for 2000. *Atmospheric Environment*. 2006; 40(22):4048–4063.
31. CDIAC. [cited 2009 August 10] Carbon Dioxide Information Analysis Center. 2009. Available from: http://cdiac.ornl.gov/trends/emis/tre_prc.html
32. West JJ, Fiore AM, Horowitz LW, Mauzerall DL. Global health benefits of mitigating ozone pollution with methane emission controls. *Proc Natl Acad Sci U S A*. 2006 Mar 14; 103(11):3988–3993. [PubMed: 16537473]
33. Bond TC, Streets DG, Yarber KF, Nelson SM, Woo JH, Klimont Z. A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research-Atmospheres*. 2004 Jul 24.109(D14) -.
34. Xie, J.; Liebenthal, A.; Warford, JJ.; Dixon, JA.; Wang, M.; Gao, S., et al. Addressing China's water scarcity: recommendations for selected water resource management issues. Washington DC: World Bank; 2009.
35. Wu KS, Huo X, Zhu GH. Relationships between esophageal cancer and spatial environment factors by using Geographic Information System. *Sci Total Environ*. 2008 Apr 15; 393(2–3):219–225. [PubMed: 18243281]
36. World Bank. Cost of Pollution in China: Economic Estimates of Physical Damages. Washington, DC: World Bank; 2007.
37. Zhang R, Li H-x, Wu X, Fan F, Sun B, Wang Z, et al. Current situation analysis on China's rural drinking water quality. *Journal of Environmental Health*. 2009; 26(1):3–5.

38. Liang S, Yang C, Zhong B, Qiu D. Re-emerging schistosomiasis in hilly and mountainous areas of Sichuan, China. *Bull World Health Organ*. 2006 Feb; 84(2):139–144. [PubMed: 16501732]
39. Smith AH. Hexavalent chromium, yellow water, and cancer: a convoluted saga. *Epidemiology*. 2008 Jan; 19(1):24–26. [PubMed: 18091414]
40. SEPA. State of the Environment Report. Beijing, China: State Environmental Protection Administration; 2006.
41. OECD. Environmental Performance Reviews: China. Beijing, China: Organisation for Economic Co-operation and Development; 2007.
42. Zhang L. Investigation on drinking water safety in China in 2006. *Journal of Environmental Health*. 2007; 24(8):595–597.
43. Gleick, P. The World's Water 2008–2009: The Biennial Report on Freshwater Resources. Washington D.C: Island Press; 2008. China and Water; p. 402
44. Chorus, I.; Bartram, J., editors. Toxic cyanobacteria in water: a Guide to their public health consequences, monitoring and management. London: E&FN Spon; 1999.
45. Ezzati M, Singer B, Kammen D. Towards an integrated framework for development-environment policy: the dynamics of environmental Kuznets curves. *World Development*. 2001; 29(8):1421–1434.
46. Gakidou E, Oza S, Vidal Fuertes C, Li AY, Lee DK, Sousa A, et al. Improving child survival through environmental and nutritional interventions: the importance of targeting interventions toward the poor. *Jama*. 2007 Oct 24; 298(16):1876–1887. [PubMed: 17954539]
47. Ministry of Health. National Environment and Health Action Plan (2007–2015). Beijing, China: 2007.
48. Hedley AJ, Wong CM, Thach TQ, Ma S, Lam TH, Anderson HR. Cardiorespiratory and all-cause mortality after restrictions on sulphur content of fuel in Hong Kong: an intervention study. *Lancet*. 2002 Nov 23; 360(9346):1646–1652. [PubMed: 12457788]
49. UNEP. The Songhua River Spill, China, Field Mission Report. Paris, France: United Nations Environment Programme, Division of Technology, Industry and Economics; 2005.
50. Wang, M.; Zhu, T.; Zheng, J.; Zhang, RY.; Zhang, SQ.; Xie, XX., et al. *Atmos Chem Phys*. Use of a mobile laboratory to evaluate changes in on-road air pollutants during the Beijing 2008 Summer Olympics. in press.

Panel 1: Industrial disaster: the Songhua River incident

Perhaps the most important recent industrial disaster in China occurred on the upper reach of the Songhua River, the largest tributary of the Heilong River which forms the border between northeastern China and Russia. The river serves as the primary drinking water source to Harbin, China's 10th largest city, and is subject to extensive industrial emissions along its length. More than 130 organic contaminants have been detected in Songhua waters (including 44 toxins classified as priority pollutants by the US EPA). An explosion on November 13, 2005 at a chemical plant led to the release of more than 100 tons of benzene, aniline and nitrobenzene into the Songhua. Data from samples collected more than 10 days later revealed a nitrobenzene concentration more than 33 times the permissible limit for surface water under Chinese law.⁴⁹ For four days, authorities shut down the drinking water system serving Harbin's 4 million residents, and municipal and residential groundwater supplies along the river's edge were taken offline as the 150 km contaminant plume passed by.⁴⁹

The Songhua event highlighted the vulnerability of key drinking water resources and the State Environmental Protection Administration has responded vigorously. Risk assessments and inspections have been conducted at hundreds of industrial facilities along major rivers throughout China, resulting in plant closures and mitigation activities at hazardous sites.^{36, 43} To improve accountability for the protection of water and other environmental resources, local and national environmental protection authority has been consolidated under a new Ministry-level agency, replacing a system that relied heavily on regional environmental protection bureaus that lacked effective coordination and oversight.⁴³ Looking forward, China has included the safeguard of water resources as a major feature of the 11th Five Year Plan, calling for further emission reductions and ambitious source protection measures, activities which may go a long way towards protecting the public from toxic exposures that, while currently unmeasured, are crucial to stemming pervasive chronic disease in China.⁴¹

Panel 2: Air pollution abatement for the 2008 Beijing Olympics

Since 1998, the Beijing municipal government has launched 14 phases of air pollution control, resulting in a gradual increase in the number of blue sky days each year. Yet this improvement was being undermined by rapid increases in energy consumption and the number of vehicles in Beijing. Improving air quality to meet international standards and public expectations during the 2008 Olympics posed an enormous challenge for the Chinese government.

Improving Beijing's ambient air quality requires not only the control of local sources but also the reduction of emissions in a large region surrounding the capital, as regional pollution contributes up to 40% of particulate matter to Beijing's air. A wide range of unprecedented air pollution measures, both at the local and regional scale, were undertaken.⁵⁰ The nearby city of Tianjin and provinces of Hebei, Shandong, Shanxi, and Inner Mongolia all took aggressive action, including an energy shift away from coal towards natural gas and other cleaner fuels, relocation of high-polluting factories, implementation of strict motor vehicle emission standards, and the installation and operation of pollution prevention and control devices. Many of these large scale actions were implemented years prior to the Olympics and were maintained after the event concluded.

In the weeks leading up to the Games, some temporary and intensive control measures were enacted. In Tianjin and Hebei province, for instance, traffic control measures, temporary closure of high-polluting industrial facilities and limitation of construction activities were implemented. Beijing took what would be the most noticeable measure, removing approximately one-half (1.5 million) of all cars from the roadway from July 20 to September 20, 2008, by alternating driving days between vehicles with even and odd license plate numbers.

Air quality in Beijing was substantially improved during the Olympics (August 8–24, 2008); the daily average concentrations of sulfur dioxide, carbon monoxide, nitrogen dioxide, and PM₁₀ were reduced by 46.7%, 42.9%, 57.4%, and 53.7%, respectively, compared to the same period in 2007, according to the 2008 Communiqué on the Environmental Status of Beijing. This drastic reduction in pollution during the Beijing Olympics provides a unique example of how a massive environmental intervention can succeed when supported by strong political will and public interest. Research findings on the health benefits from this drastic improvement of air quality have started to appear in the scientific literature, and the public health legacy of the Beijing Olympics will be felt far beyond the event itself.

Figure 1.

The trends in energy production and emissions of sulfur dioxide (SO₂) and dust in China, from 1998 to 2008. Energy production data are from China Statistical Year Book 2008, and emission data are derived from Chinese Environmental Year Book, 1998–2008.

Figure 2.

A comparison of total global, USA, China and Western European annual carbon dioxide (CO₂) emissions (left) and per capita annual carbon dioxide emissions (right).³¹

Figure 3.

Surface water quality in seven river systems and thirteen major lakes in 2008. Rivers are labeled with bars representing the distribution of water quality based on monitoring results in each river system, and water quality of major lakes are labeled with filled circles. Grades represent official water quality classifications based on China's Surface Water Environmental Quality Standard as reported by the Ministry of Environmental Protection's Bulletin of China's Water Conditions, 2009.

Figure 4.
Trends in the incidence of cholera, dysentery, and typhoid/paratyphoid from 1985 to 2007.
Data were derived from Ministry of Health's annual Health Yearbook, 1985 – 2008.

Table 1

Key traditional, modern and emerging environmental risk factors in China

Environmental risk factors		Major health effects	Populations at risk/affected
Traditional	Indoor air pollution from solid fuel combustion	Chronic obstructive pulmonary diseases, acute lower respiratory infection, lung cancer, possibly low birth weight ⁸	Almost all rural residents (~740 million); ~35% of urban residents (~200 million); estimated 420,000 premature deaths annually ⁸
	Unsafe drinking water and poor sanitation	Infectious diseases (e.g. diarrhea, hepatitis A, typhoid, schistosomiasis) ^{9–11}	> 40% of rural residents (230 million); > 6.2% urban residents (46 million) ^{9–10}
Modern	Outdoor air pollution	Cardio-respiratory mortalities and morbidities, acute respiratory infections and symptoms, lung cancer, possibly adverse birth outcomes ^{9–10}	Almost all urban residents (~580 million); rural residents living near industrial facilities and cities; an estimated 470,000 premature deaths in 2000 ^{12–14}
	Industrial water pollution	Cancers of the digestive system (e.g., stomach, liver, esophagus, colorectal) ^{10, 15}	Affected population unknown; an estimated 11% of total digestive system cancer cases (about 954,500 annually) ¹⁵
Emerging	International transport of persistent chemical containments	Cardio-respiratory diseases from particulate matter and ozone, neurological damage from mercury exposure ^{13–14, 16}	Persons living downwind of China (e.g., Japan, Korea, United States) ^{17–18}
	Climate change	Deaths due to heat waves, floods, fires and droughts; increased infectious diseases ^{19–21}	Diverse populations throughout China, including coastal communities, water scarce regions and urban populations; global populations