Review

Environmental health in China: progress towards clean air and safe water

Junfeng Zhang, Denise L Mauzerall, Tong Zhu, Song Liang, Majid Ezzati, Justin V Remais

Lancet 2010; 375: 1110–19

See **Comment** page 1055

University of Medicine and Dentistry of New Jersey, School of Public Health, Piscataway, NJ, USA (Prof J Zhang PhD); **Princeton University Woodrow Wilson School of Public and International Affairs and Department of Civil and Environmental Engineering, Princeton, NJ, USA** (D L Mauzerall PhD); **State Key Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering and Centre for Environment and Health, Peking University, Beijing, China** (Prof T Zhu PhD); **Ohio State University College of Public Health, Columbus, OH, USA** (S Liang PhD); **Harvard University School of Public Health, Boston, MA, USA** (M Ezzati PhD); **and Department of Environmental and Occupational Health, Rollins School of Public Health, Emory University, Atlanta, GA, USA** (J V Remais PhD)

Correspondence to: Dr Justin V Remais, Department of Environmental and Occupational Health, Rollins School of Public Health, Emory University, Atlanta, GA 30322, USA **justin.remais@emory.edu**

Environmental risk factors, especially air and water pollution, are a major source of morbidity and mortality in China. Biomass fuel and coal are 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 is high. At the same time, China is rapidly industrialising with associated increases in energy use and industrial waste. Although economic growth from industrialisation has improved health and quality of life indicators, it has also increased the release of chemical toxins into the environment and the rate of environmental disasters, with severe effects 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 troubles, with potentially catastrophic outcomes from major shifts in temperature and precipitation. Facing the overlap of traditional, modern, and emerging environmental dilemmas, China has committed substantial resources to environmental improvement. The country has the opportunity to 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 ten-fold increase in gross domestic product during the past 15 years—has pulled hundreds of millions of people out of poverty.[1] However, environmental effects of economic growth are of increasing concern to the country's citizens and policy makers, and the unaddressed health effects of environmental pollution pose major policy challenges. Despite the well established links between adverse health outcomes and poor air and water quality,[2] many cities have air pollution levels well above health-based standards,[3] and half of China's water resources are considered too polluted for human use.[4] These and other environmental risks lead to an estimated 2·4 million premature deaths every year from cardiopulmonary and gastrointestinal diseases, cancers, and other diseases or 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.

Search strategy and selection criteria

We searched PubMed for English language papers, and China National Knowledge Infrastructure and Wanfang for Chinese language papers. We used the search terms "environmental health", "air pollution", "water pollution", "soil pollution", "residential coal use", "biomass fuel", and "climate change" combined with the term "China". We largely selected publications from the past 10 years. We manually reviewed Chinese health and environmental statistical yearbooks published over the past 15 years, and government reports over the past 5 years. We accessed the national notifiable infectious diseases database for morbidity and mortality data in 1985–2007.

Substantial progress has been made to reduce the burden of disease associated with traditional environmental exposures, such as diarrhoea caused by contaminated drinking water and poor sanitation. China is taking a technological approach to improve environmental quality, through development of the world's largest high-speed rail network to provide clean, efficient transport; stringent vehicle fuel efficiency requirements that exceed the US standards; and commitment 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 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.[6] However, diseases associated with environmental factors remain a major source of ill health, especially in poor populations. Substantial health disparities between the poor and wealthy are determined partly 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 that are associated with industrialisation and urbanisation include outdoor air pollution and industrial waste. These risks co-exist with several emerging risk factors, such as climate change and international transport of air pollutants. Despite frequent reference to China's environmental risks in scientific publications and popular media, little attention has been paid to potential policy solutions across the diverse sources of pollution and exposed populations. Indeed, a comprehensive analysis of environmental indicators and health outcomes is absent. Here, we review Chinese

	Major health effects	Populations at risk or affected
Traditional		
Indoor air pollution from solid fuel combustion	Chronic obstructive pulmonary disease, acute lower respiratory infection, lung cancer, possibly low birthweight[8]	Almost all rural residents (~740 million); about 35% of urban residents (~200 million); estimated 420 000 premature deaths yearly[8]
Unsafe drinking water and poor sanitation	Infectious diseases (eg, diarrhoea, hepatitis A, typhoid, schistosomiasis)[9–11]	>40% of rural residents (>296 million); >6·2% urban residents (46 million)[9,10]
Modern		
Outdoor air pollution	Cardiorespiratory 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[12–15]
Industrial water pollution	Cancers of the digestive system (eg, stomach, liver, oesophagus, or colorectal cancer)[10,16]	Affected population unknown; an estimated 11% of total digestive system cancer cases (~954 500 yearly)[16]
Emerging		
International transport of persistent chemical contaminants	Cardiorespiratory diseases from particulate matter and ozone, neurological damage from mercury exposure[13,14,17]	People living downwind of China (eg, Japan, Korea, and USA)[15,18]
Climate change	Deaths due to heat waves, floods, fires, and droughts; increased infectious diseases[19–21]	Throughout China, including coastal communities, water-scarce regions, and urban populations; global populations

Table: **Traditional, modern, and emerging environmental risk factors in China**

environmental data and yearly health statistics published over the past 20 years to address this gap. We describe the change in environmental risks, and consider the major sources of air (including greenhouse-gas pollutants) and water pollution, and the associated health outcomes both within—and downwind of—China (table). We discuss recent progress and challenges that remain for environmental health issues, and emphasise policy initiatives that are key to the reduction of China's environmental health risks today, while ensuring a safer and healthier future environment.

Environmental risks

China is at a stage of development at which environmental risks are changing rapidly, shifting from traditional to modern sources. In many large cities, household coal use is declining, while new sources of indoor air pollution are increasing, such as formaldehyde and other synthetic chemicals released from building materials. Many communities are still exposed to risks from traditional and modern pollutants, neither of which shows signs of abatement. For example, residents on the periphery of Shaoguan City in Guandong province remain reliant on the traditional and hazardous practice of burning wood and crop residue indoors without chimneys 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 past 30 years, the overlap of traditional and modern risks has been complicated by the largest ever migration of people from rural to urban areas. From 1978 to 2007, the proportion living in urban areas increased from 18% to 45%—an increase of nearly 422 million urban dwellers.[9] Of these people, more than 140 million moved from villages to cities seeking work.[25] With this migration comes a complex trade-off 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 health care, and poor housing conditions and their related communicable diseases.[25,26] Additionally, with the rising health effects of global climate change, environmental risks in China are no longer restricted to local or national emissions, but now have a substantial international component. Moreover, many other neglected issues have emerged such as occupational exposures, land use change, disposal of electronic waste, and food safety, which are expected to lead to widespread health problems. The scarcity of systematically collected data for these issues prohibits a credible risk analysis.

Air pollution

Health risks result when hazardous chemical or biological agents are added to indoor or outdoor air. Indoor combustion of solid fuels in simple household stoves releases large quantities of pollutants, which frequently leads to concentrations of respirable particles and carbon monoxide more than ten-times higher than health-based standards.[8] Similarly, fossil fuel combustion from industrial, transportation, and residential sectors, and burning of agricultural wastes, results in air quality in modern cities and adjacent regions that is among the worst in the world.

Indoor air pollution from burning solid fuels is one of the main environmental health risk factors, and leads to about 420 000 premature deaths every year.[8] The major health outcomes associated with air pollution include chronic obstructive pulmonary disease (COPD), acute lower respiratory infection, and lung cancer.[8] COPD is responsible for 1·3 million deaths yearly in China, and solid fuel use increases COPD incidence more than

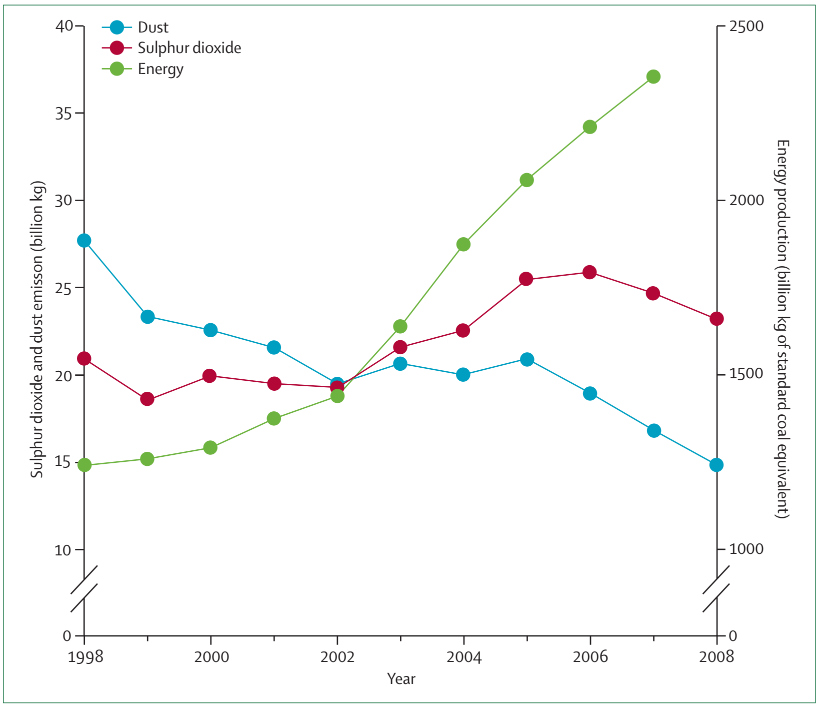

Figure 1: **Energy production and emissions of sulphur dioxide and dust in China, from 1998 to 2008**
Data from the National Bureau of Statistics of China.[9,30]

three-fold.[8] Likewise, solid fuel use is a major risk factor for acute lower respiratory tract infections, which predominantly kill young children and therefore contribute more lost life-years per death than do diseases that affect older people. Indoor air pollution from solid fuel combustion results in an especially high disease burden because many people are exposed to consistent, high levels of pollutants over their lifetimes. More than half of China's population remains 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. Furthermore, about 100 counties (out of a total of roughly 1500) in China possess natural deposits of coals that contain high concentrations 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 southwest China, and dental and skeletal fluorosis in more than 10 million people in Guizhou province.[8]

Reduction of exposure to coal smoke is a major public health objective, and can substantially improve health. For instance, adding chimneys to stoves led to more than 50% reductions in risk of lung cancer and COPD in Yunnan province.[8] Yet even after much investment by the national improved stoves programme, improved indoor air quality remains an elusive goal in China.

Since the early 1980s, China's national improved stoves programme has introduced more than 180 million stoves, which is 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 diversion of pollutants outdoors, and thus lead to reduced indoor pollutant concentrations. However, pollutant concentration reduction varies substantially with the type of improved stove.[8] Since the programme ended in the mid-1990s, the situation seems to be worsening as coal use in rural areas rises, and is more often burned in stoves without chimneys. Piped gas and liquefied petroleum gas offer some hope, but widespread use of these clean fuels in rural households is unlikely to occur soon because of cost and supply issues. Hence, policy and technical interventions to make use of solid fuels less polluting are still of prime public health importance.

Outdoor air pollution in China originates from many sources, including residential and industrial coal combustion, a growing transport sector, chemical releases from industry, outdoor burning of agricultural waste, and dust from construction, roads, and deserts. About 70% of electricity is generated by burning coal, most of which has a high sulphur content. High concentrations of sulphur dioxide and particulate matter are emitted when sulphur-rich coal is burnt. These emissions contribute to the formation of acid rain and sulphurous smog, which plagued major industrial centres in Europe and North America (eg, London, UK; Pittsburgh, PA, USA; and the Meuse Valley, Belgium) in the early 20th century. At the same time, the number of motor vehicles in Chinese cities is rapidly increasing, with more than 1000 vehicles added to Beijing's streets every day—at the end of 2008, Beijing had 3·5 million vehicles. Emissions from these vehicles lead to the formation of photochemical smog that contains respirable particles and ozone, not only within the city but also in the adjacent regions. Ozone concentrations within and downwind of major Chinese cities frequently exceed WHO air quality guidelines.[27] Yearly mean density of respirable particles in Chinese megacities such as Beijing and Shanghai often approach or are greater than 100 μg/m³, which is about twice as high as Tokyo, Japan, nearly four times as high as New York City, NY, USA, and four times the WHO guideline.[28]

In 2000, outdoor air pollution led to about 470 000 premature deaths in China.[12,15] Exposure to outdoor air pollutants (mainly respirable particles, ozone, and nitrogen dioxide) has been associated with lung cancer, cardiorespiratory diseases, and possibly low birthweight.[13,14] The economic cost of mortality and morbidity that results from outdoor air pollution in a typical Chinese city was about 10% of that city's gross domestic product in 2000, and, dependent on future technology and policies, this cost is predicted to range from 8% to 16% by 2020.[12]

Other health consequences are indirect. The outflow of pollution from urban to rural regions, for example,

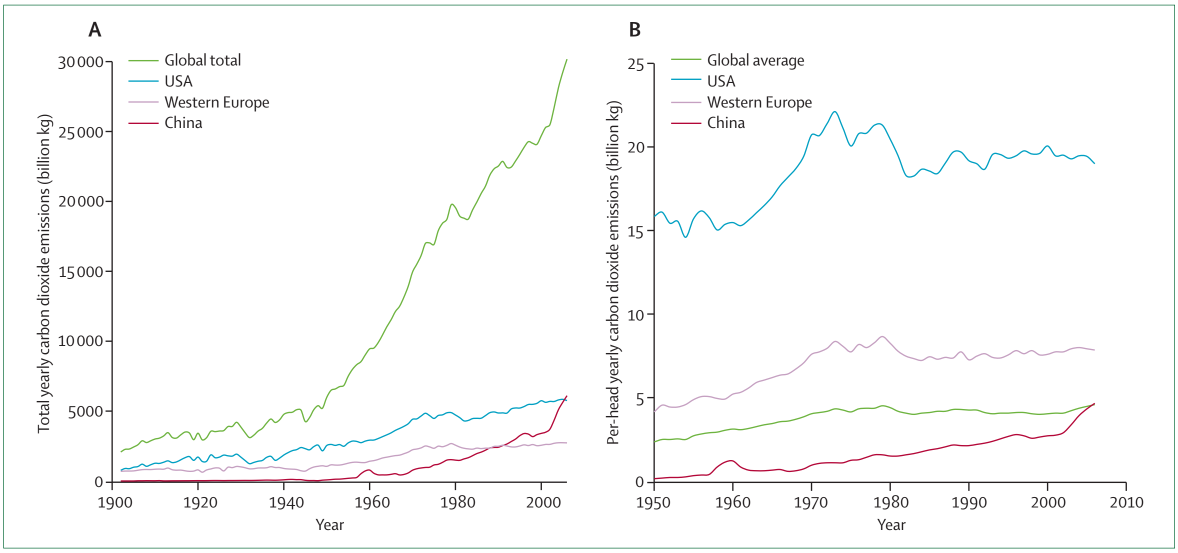

Figure 2: **Total yearly worldwide, US, Chinese, and western European carbon dioxide emissions (A) and per-head yearly carbon dioxide emissions (B)**
Data from Boden and colleagues.[32]

increases concentrations of ozone in agricultural areas and depresses crop yields, threatening China's food security.[29] Since China opens a coal-fired power plant every week and burns more coal than the next seven largest consumers in the world combined, the control of outdoor air pollution should be a top policy priority for China.

China's efforts to reduce outdoor air pollution have focused on reduction of sulphur dioxide and dust concentrations from the energy and industrial sectors. China is installing and operating sulphur scrubbers on most new power plants, which has decreased national emissions of sulphur dioxide and dust since 2005, even as energy production has risen (figure 1). Similarly, a national policy requiring lead-free petrol 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, which has raised public awareness and concern. China's 11th 5-year plan could help to address major outdoor air pollution challenges by setting targets for reduction of energy consumption per unit gross domestic product by 20% by 2010, and an increase in renewable energy to 10% of total energy sources. However, because ambient concentrations of air pollutants in most Chinese cities are currently several times higher than in typical cities in developed countries, major long-term challenges remain for improvement of China's outdoor air quality.

Air pollutants are transported between countries and continents, imposing health effects far from the point of emission.[18] Satellite findings of dust transport across the Pacific ocean show that emissions in Asia reach surface locations in the USA 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 about a month. Thus, pollutants with lifetimes of a few weeks or more can affect air quality in downwind countries.[15,18]

Emissions of inorganic mercury, which has an atmospheric residence time of about a year, are widely recognised to be transported worldwide.[31] 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 or swordfish). Exposure to methyl mercury impairs neurological development, especially in fetuses, infants, and children, and can adversely affect developing brain and nervous tissue.[17] As much as two-thirds of worldwide emissions of inorganic mercury comes from coal combustion, with China responsible for about 28% of the total (600 000 kg per year).[31] Consumption of contaminated fish is the main source of human exposure to mercury,[17] and complex fish migration patterns mean that people both near and far from emission sources can be exposed to dangerously high concentrations of mercury.

China's economic growth has been largely driven by 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 emissions per head in China are at the global average (each person in the USA emits about four times as much as do people in China), China surpassed the USA as the country emitting the most carbon dioxide in 2006 (figure 2). China and the USA are 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, Denmark.

For the **United Nations Framework Convention on Climate Change** see http://unfccc.int/2860.php

For the **Intergovernmental Panel on Climate Change assessment reports** see http://www.ipcc.ch

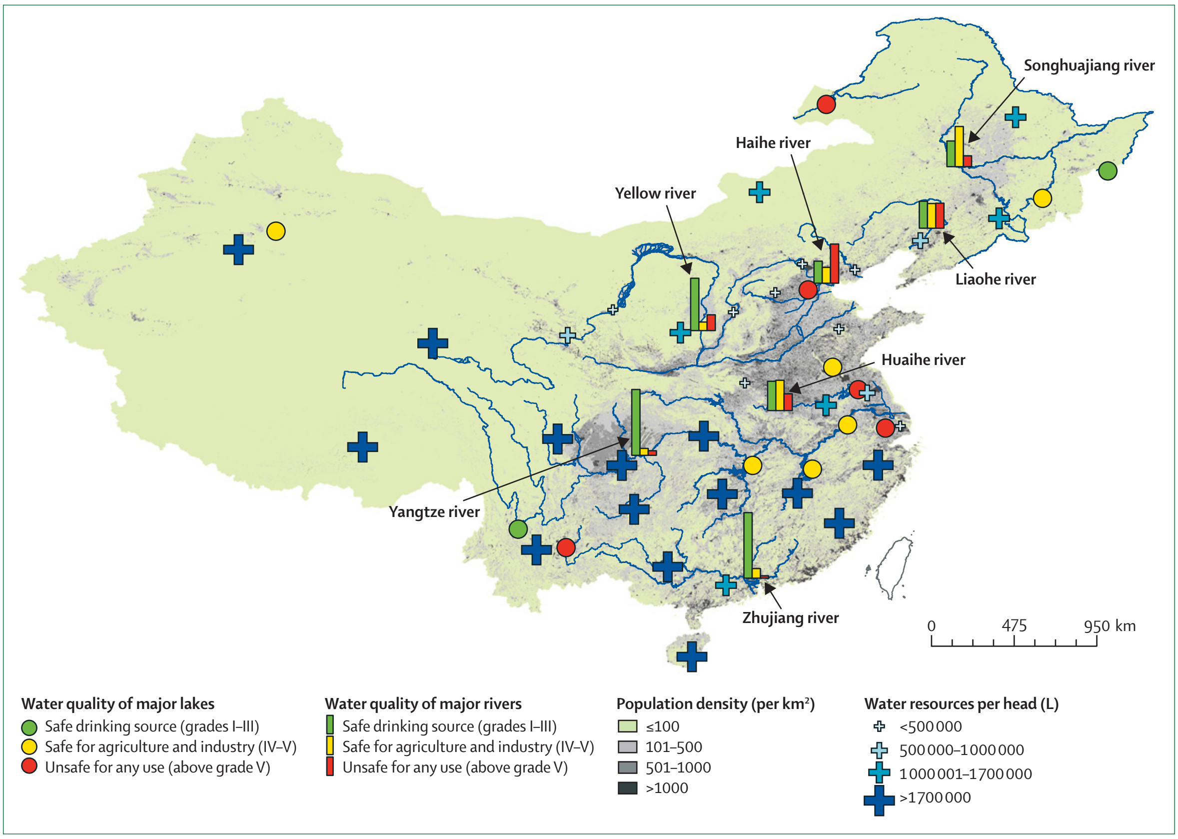

***Figure 3*: Surface water quality in seven river systems and 13 major lakes in 2008**

Rivers are labelled with bars representing the distribution of water quality based on monitoring results in each river system, and water quality of major lakes is labelled 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 of the People's Republic of China.[36]

China is also a large emitter of methane, the second most important greenhouse gas, which is emitted from rice paddies, landfills, coal mines, leaky gas distribution systems, and a range of natural sources. In addition to being a direct greenhouse gas, methane is a precursor for ozone and contributes to the rising worldwide background concentration of surface ozone and associated premature mortalities.[33] Similarly, China is responsible for about 30% of global black carbon emissions from contained combustion.[34] Sources of particular importance for climate and health include diesel engines and residential and small-scale industrial coal combustion. A rise in the number of diesel engines in the transport sector potentially increases that fraction.

Black carbon, a key component of soot, is a major contributor to global warming and could 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. However, sulphate particles, formed from sulphur dioxide released from coal combustion, cool the climate,[21] and thus any success in reduction of sulphur dioxide emissions, although of direct benefit to health, will allow the warming effect of long-lived gases to be felt more strongly.

Water pollution

China's water resources are inadequate, amounting to less than 2 156 000 L per head per year, slightly greater than India's 1 720 000 L, but only a fifth of the US supply per head and less than a quarter of average world supply.[35] Furthermore, China's water resources are very unevenly distributed (figure 3). The heavily populated northern river basins contain 44% of the population and 65% of its cultivated land, but have less than 13% of the water supply—only 757 000 L per head per year—which is substantially less than the amount commonly defined as water scarcity (1 000 000 L per year).[35] Water shortages compel populations to use contaminated sources, which might explain associations between water scarcity and health effects, such as oesophageal cancer.[37] As industrial, agricultural, and municipal uses of water compete for an increasingly restricted supply, pollution of these resources will exacerbate shortages.

A high number of lakes and major rivers in China are classified as severely polluted, with only half of China's 200 major rivers and less than a quarter of its 28 major

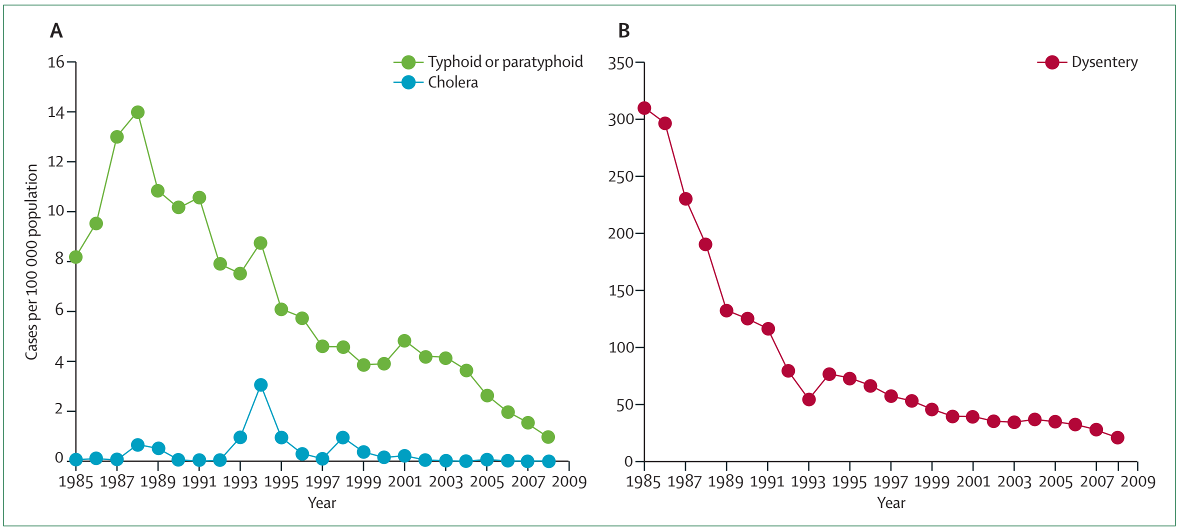

Figure 4: **Incidence of cholera and typhoid or paratyphoid (A) and dysentery (B), from 1985 to 2008**
Data from the National Bureau of Statistics of China.[9]

lakes and reservoirs suitable for use as drinking water after treatment.[4] Water pollution varies widely across the country (figure 3), and is governed by geographical differences in population, industrialisation, and treatment capacity. Nationwide, more than 300 million people rely on hazardous drinking water sources, costing China (a crudely, but conservatively estimated) 2% of its rural gross domestic product from diseases associated with microbial and industrial pollutants.[38]

Water pollution is especially severe in rural areas, where few drinking water and sanitation services were in place until the late 1980s and early 1990s, when China's Patriotic Health Campaign invested enormous resources in improvement of these services. However, coverage remains low. A national survey in 2006 of more than 60 000 rural households across China found only about half had access to a centralised public water supply; the remainder relied on untreated hand pump, well, or surface-water sources.[39] Meanwhile, nearly half of more than 7000 water samples from a range of rural supplies were unsafe for drinking, many of which were contaminated with untreated sewage.[39] Although the immediate risk of faecal to 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, can lead to liver cancer.[40]

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—such as schistosome parasites—have re-emerged in regions that had previously achieved elimination.[41] On the basis of the latest estimates of the Ministry of Health, rural coverage of improved sanitation in 2007 was 57%, and most waste from both improved and unimproved lavatories in these regions was returned untreated to the environment as fertiliser. Major investments are on the horizon, and the government has set the goal of 65% sanitation coverage in rural China by the end of 2010.

Access to piped water increased from 30% of the population in 1985 to 77% in 2007 and, despite a massive increase in urban population, access for urban residents reached nearly 94% in 2007.[9,10] Partly as a result of this increase in access to piped water, 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 or paratyphoid, other infectious diarrhoea, and schistosomiasis) has declined steadily over the past 20 years.[10] In 2008, the incidence of cholera, dysentery, typhoid, and paratyphoid was 25 per 100 000 population, with 63 deaths reported, which was down from 319 per 100 000 with 2610 deaths in 1985 (figure 4).[10] Although the reporting system is thought to underestimate actual incidence (for example, under-reporting for dysentery can vary from 44% to 71% across the country),[11] these gains are impressive, and will probably be sustained with the Ministry of Health's plans to initiate a national water quality surveillance network.[10]

Reliance 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 such as nitrate, nitrite, and chromium are major risk factors for digestive system cancers (ie, stomach, liver, oesophageal, and colorectal cancer). These cancers have the highest mortality rate of malignant neoplasms in China at 73 per 100 000 cases in 2005.[10] Estimates attribute about 11% of digestive cancer cases to chemical contaminants in drinking water, indicating that the disease burden from industrial water

Panel 1: **Songhua river industrial disaster**

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 that forms the border between northeastern China and Russia. The river serves as the primary drinking water source to Harbin, China's tenth 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 regulated by the US Environmental Protection Agency as priority pollutants, on the basis of their toxicity, persistence, or other hazardous characteristics). An explosion on Nov 13, 2005, at a chemical plant led to the release of more than 100 000 kg 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.[43] For 4 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.[43]

The Songhua event highlighted the vulnerability of key drinking water resources, and the State Environmental Protection Administration responded vigorously. Risk assessments and inspections have been done at hundreds of industrial facilities along major rivers throughout China, resulting in plant closures and mitigation activities at hazardous sites.[38,44] To improve accountability for the protection of water and other environmental resources, local and national environmental protection authorities have 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.[44] China has included safeguard of water resources as a major feature of the 11th 5-year plan, calling for further emission reductions and ambitious source protection measures, which might go a long way towards protecting the public from toxic exposures that—although currently unmeasured—are crucial to stemming pervasive chronic disease in China.[45]

pollution, oil and gas industries, manufacturing, and other sources, already poses major challenges for the health of China's citizens.[16]

Growth in China's industrial contamination shows few signs of abatement. The past 20 years have witnessed unregulated and increased industrial discharges and excessive use of fertilisers and pesticides in agricultural areas. In northern China, water scarcity has exacerbated these emissions, forcing farmers to apply waste water as irrigation to about 40 000 km² of agricultural land. This results in contamination of food by heavy metals such as mercury, cadmium, lead, copper, chromium, and arsenic, and provides another route of exposure and can transfer water pollutants to soil.

Reliable data for industrial emissions are seldom made public, and national assessments of drinking water quality are rare—the last was undertaken in 1988. When nationwide surveys are done, they are often restricted in scope, centre solely on surface water, and stop short of estimations of risks to public health. Furthermore, investigation 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.[38,42] Improved environmental monitoring, industry transparency, and new regulatory initiatives that could help to resolve these difficulties are being driven by citizen discontent with industrial accidents (panel 1), and would improve the base of evidence for future policy.

Recent progress to limit industrial water pollution includes large reported reductions (60–70% by mass) in yearly emissions of arsenic and mercury to water,[9,46] and construction of more than 60 000 industrial waste water treatment plants.[45] Yet in the absence of monitoring and oversight, improvements to water quality from these efforts have not been documented. China's water-quality monitoring system is complex. Public health and environmental regulators and suppliers participate, but data are rarely made public and monitoring requirements often go unmet. A national survey in 2006 of several thousand suppliers revealed more than a quarter of municipal plants and half of private plants were not properly monitoring the quality of the drinking water they provided.[47] 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 various points, including at sources, distribution systems, and point of use, along with human health status.[10] The Ministry of Health intends to expand this programme nationally: an ambitious plan that could rapidly improve the safety of China's drinking water resources.

China's vulnerability to climate change is, in part, an exacerbation of existing environmental risks and their health consequences. For instance, there is substantial 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 that supply much of the country with water. Rainfall is declining in northern China by 20–40 mm per decade,[35] and projections show the uneven north–south precipitation distribution will intensify under future climate scenarios.[41] These projections show increased frequency of extreme precipitation in southern China, leading to flooding and an accompanying loss of life—such as the floods in 2007 that led to more than 1200 deaths, and a loss of 120 000 km² of crops and 1 million houses.[44]

These conditions are made worse when combined with increased temperatures, which promote the survival, replication, and transmission of waterborne pathogens, algae, and disease-carrying vectors. Algal blooms in lakes and reservoirs contaminate drinking water with toxic microcystins, and lead to acute effects such as rashes, diarrhoea, nerve and liver damage, and chronic outcomes that include liver cancers.[40] These blooms are already a major hazard, as was seen when a bloom in Taihu lake contaminated the water supply serving millions of people 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. Although much 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]

Improvement of environmental health policies in China

A common view of the relation 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), which is referred to as the environmental Kuznets curve. However, both the initial worsening and subsequent improvement of environmental quality are not inevitable consequences of development but, rather, are highly affected by technology and policy choices.[48] 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, there is a 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 growing inequalities in income, health, access to clean water, sanitation, and cleaner fuels.[7] Thus, despite growth in aggregate national income, the traditional environmental risk factors continue to severely affect the health of poor and marginalised communities.[7] Each unit of intervention that reaches a poor household is likely to have a larger effect than if it reaches an affluent household,[49] and thus programmes that disproportionately benefit the poor are essential, such as subsidies for high-quality stoves and investment in rural water and sanitation services.

China has shown 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 (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 towards industrial productivity might be partly responsible for limiting access to clean fuels in low-income rural households and for increases in some urban air pollutants. Similarly, factories and enterprises owned by local governments might be the largest polluters in some areas.

Panel 2: Air pollution abatement for the 2008 Beijing Olympics

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

Improvement of Beijing's ambient air quality needs not only the control of local sources but also the reduction of emissions in a large region surrounding the capital, because 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 before 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 provinces, 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, and removed about half (1·5 million) of all cars from the roads from July 20, 2008, to Sept 20, 2008, by alternating driving days between vehicles with even and odd licence plate numbers.

Air quality in Beijing was substantially improved during the Olympics (Aug 8–24, 2008). The daily average concentrations of sulphur dioxide, carbon monoxide, nitrogen dioxide, and particulate matter of 10 μm or less were reduced by 46·7%, 42·9%, 57·4%, and 53·7%, respectively, compared with 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 improvement of air quality have started to appear in scientific publications, and the public health legacy of the Beijing Olympics will be felt far beyond the event itself.

A greater emphasis on regulatory enforcement is needed, to include substantial fines and criminal penalties, and systems to objectively assess the success of specific regulatory actions must be instituted. China's recently released first National Environment and Health Action Plan[51] emphasises the need to coordinate activities across many sectors and ministries. It identifies coordinated and shared data collection and environmental monitoring as a crucial feature of future environmental health policies.

Finally, successful past polices to reduce environmental risks should form the basis for reform. Examples such as Hong Kong's 1990 low-sulphur fuel law, which led to an estimated increase in life expectancy of 20 days for women and 41 days for men,[52] and Beijing Olympic air-quality polices, 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 5-year plan, and reiterating in Copenhagen its intention to reduce greenhouse-gas emissions per unit gross domestic product irrespective of the actions of other countries. These environmental goals will have a substantial effect if achieved alongside a firm commitment from the Chinese Government to formulate, implement, and enforce effective environmental health policies.

Contributors

JVR, JZ, and DLM conceptualised and coordinated the preparation of the Review. All authors participated in data analysis, discussion, and writing of the Review.

Conflicts of interest

We declare that we have no conflicts of interest.

Acknowledgments

We 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 a National Institute of Environmental Health Sciences Center Grant (#P30ES 05022) awarded to the University of Medicine and Dentistry, New Jersey 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 a National Institutes of Health/National Institute of Allergy and Infectious Diseases grant (R01 AI068854) to University of California, Berkeley. JVR is supported by the National Institutes of Health/National Science Foundation Ecology of Infectious Disease Program (grant 0622743) and Emory University's Global Health Institute.

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. Special Report 15: health effects of outdoor air pollution in developing countries of Asia. Boston, MA: Health Effects Institute, 2004.
4 MEP. Bulletin of China's environmental conditions. Beijing: Ministry of Environmental Protection, 2009.
5 WHO. Quantification of the disease burden attributable to environmental risk factors. China country profile. Geneva: World Health Organization, 2009.
6 Lopez A, Mathers C, Ezzati M, Murray C, Jamison D. Global burden of disease and risk factors. New York, NY: 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; **372:** 1493–501.
8 Zhang J, Smith KR. Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions. *Environ Health Perspec* 2007; **115:** 848–55.
9 NBSC. China statistical yearbook. Beijing: National Bureau of Statistics of China, 1986–2008.
10 Chinese Ministry of Health. 2007 health yearbook. Beijing: Ministry of Health, 2007.
11 Wang XY, Tao FB, Xiao DL, et al. Trend and disease burden of bacillary dysentery in China (1991–2000). *Bull World Health Organ* 2006; **84:** 561–68.
12 Wang X, Mauzerall DL. Evaluating impacts of air pollution in China on public health: implications for future air pollution and energy policies. *Atmos Environ* 2006; **40:** 1706–21.
13 Pope CA III, Burnett RT, Thun MJ, et al. Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. *JAMA* 2002; **287:** 1132–41.
14 Dockery DW, Pope CA III, Xu X, et al. An association between air pollution and mortality in six U.S. cities. *N Engl J Med* 1993; **329:** 1753–59.
15 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. *Atmos Environ* 2009; **43:** 2814–22.
16 WHO-UNDP. Environment and people's health in China. Geneva: World Health Organisation, 2001.
17 NAS. Toxicological effects of methylmercury. Washington, DC: National Academies Press, 2000.
18 Liu J, Mauzerall DL, Horowitz LW. Evaluating Inter-continental transport of fine aerosols: (2) global health impacts. *Atmos Environ* 2009; **43:** 4339–47.
19 Zhou XN, Yang GJ, Yang K, et al. Potential impact of climate change on schistosomiasis transmission in China. *Am J Trop Med Hyg* 2008; **78:** 188–94.
20 Campbell-Lendrum D, Corvalan C. Climate change and developing-country cities: implications for environmental health and equity. *J Urban Health* 2007; **84:** i109–17.
21 IPCC. 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. Geneva: Intergovernmental Panel on Climate Change, 2008. http://www1.ipcc.ch/ipccreports/assessments-reports.htm (accessed March 3, 2010).
22 Liu S, Zhou Y, Wang X, et al. Biomass fuels are the probable risk factor for chronic obstructive pulmonary disease in rural South China. *Thorax* 2007; **62:** 889–97.
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; **31:** 707–15.
24 Bao QS, Lu CY, Song H, 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.
25 Hu X, Cook S, Salazar MA. Internal migration and health in China. *Lancet* 2008; **372:** 1717–19.
26 Jia ZW, Jia XW, Liu YX, et al. Spatial analysis of tuberculosis cases in migrants and permanent residents, Beijing, 2000–2006. *Emerg Infect Dis* 2008; **14:** 1413–19.
27 Shao M, Tang XY, Zhang YH, Li WJ. Air and surface water pollution of city clusters in China: current situation and challenges. *Front Ecol Environ* 2006; **7:** 353–61.
28 Parrish DD, Zhu T. Clean air for megacities. *Science* 2009; **326:** 674–75.
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. *Atmos Environ* 2004; **38:** 4383–402.
30 NBSC. China environmental statistical yearbook. Beijing: National Bureau of Statistics of China, 1998–2008.
31 Pacyna EG, Pacyna JM, Steenhuisen F, Wilson S. Global anthropogenic mercury emission inventory for 2000. *Atmos Environ* 2006; **40:** 4048–63.

32 Boden TA, Marland G, Andres RJ. Global, regional, and national fossil-fuel CO_2 emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA. Oak Ridge, TN: Department of Energy, 2009.

33 West JJ, Fiore AM, Horowitz LW, Mauzerall DL. Global health benefits of mitigating ozone pollution with methane emission controls. *Proc Natl Acad Sci USA* 2006; **103:** 3988–93.

34 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. *J Geophys Res* 2004; **109:** D14203.

35 Xie J, Liebenthal A, Warford JJ, et al. Addressing China's water scarcity: recommendations for selected water resource management issues. Washington, DC: World Bank, 2009.

36 Ministry of Environmental Protection of the People's Republic of China. June 17, 2009. http://wfs.mep.gov.cn/swrkz/zhgl/200906/t20090617_152894.htm (accessed March 3, 2010).

37 Wu KS, Huo X, Zhu GH. Relationships between esophageal cancer and spatial environment factors by using Geographic Information System. *Sci Total Environ* 2008; **393:** 219–25.

38 World Bank. Cost of pollution in China: economic estimates of physical damages. Washington, DC: World Bank, 2007.

39 Zhang R, Li H-x, Wu X, et al. Current situation analysis on China's rural drinking water quality. *J Environ Health* 2009; **26:** 3–5.

40 Chorus I, Bartram J, eds. Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management. London: E&FN Spon, 1999.

41 Liang S, Yang C, Zhong B, Qiu D. Re-emerging schistosomiasis in hilly and mountainous areas of Sichuan, China. *Bull World Health Organ* 2006; **84:** 139–44.

42 Smith AH. Hexavalent chromium, yellow water, and cancer: a convoluted saga. *Epidemiology* 2008; **19:** 24–26.

43 UNEP. The Songhua river spill, China, field mission report. Paris: United Nations Environment Programme, Division of Technology, Industry and Economics, 2005.

44 Gleick P. China and water. The world's water 2008–2009: the biennial report on freshwater resources. Washington, DC: Island Press, 2008: 402.

45 OECD. Environmental performance reviews: China. Beijing: Organisation for Economic Co-operation and Development, 2007.

46 SEPA. State of the Environment Report. Beijing: State Environmental Protection Administration, 2006.

47 Zhang L. Investigation on drinking water safety in China in 2006. *J Environ Health* 2007; **24:** 595–97.

48 Ezzati M, Singer B, Kammen D. Towards an integrated framework for development-environment policy: the dynamics of environmental Kuznets curves. *World Dev* 2001; **29:** 1421–34.

49 Gakidou E, Oza S, Vidal Fuertes C, et al. Improving child survival through environmental and nutritional interventions: the importance of targeting interventions toward the poor. *JAMA* 2007; **298:** 1876–87.

50 Wang M, Zhu T, Zheng J, et al. Use of a mobile laboratory to evaluate changes in on-road air pollutants during the Beijing 2008 Summer Olympics. *Atmos Chem Phys* 2009; **9:** 8247–63.

51 Chinese Ministry of Health. National environment and health action plan (2007–2015). Beijing: Ministry of Health, 2007.

52 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; **360:** 1646–52.