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China's Environmental Challenges and Implications for the World

JIANGUO LIU[1] and PETER H. RAVEN[2]
[1]*Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, Michigan, USA*
[2]*Missouri Botanical Garden, St. Louis, Missouri, USA*

After three decades of exceptional economic growth, China has become a global economic powerhouse. As the economy has grown, though, so have China's environmental challenges, causing enormous socioeconomic consequences for China and the rest of the world. The global financial crisis has prompted China to create more domestic demand for consumption and implement massive infrastructure construction. Although China has the second-largest total gross domestic product (GDP) in the world, its per capita GDP is still much lower than per capita GDP of developed countries: there is much room for further increase in GDP and consequent environmental challenges. Despite China's many efforts to protect the environment and improve resource use efficiency, increasing environmental pollution and resource scarcity have become a severe bottleneck for sustainable development. Because of China's size, these and other challenges and opportunities have huge implications for the world. However, literature related to China's various environmental challenges and rapid changes is scattered. In this article, we outline China's socioeconomic transformation, synthesize China's environmental challenges and their interrelationships, illustrate impacts of environmental challenges on human well-being in China and beyond, and offer a systems approach to addressing environmental sustainability.

Address correspondence to Jianguo Liu, Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48823-5243; Tel.: (517) 432-5025; Fax: (517) 432-5066; E-mail: jliu@panda.msu.edu; or Peter H. Raven, Missouri Botanical Garden, St. Louis, MO 63166-0299, USA; Tel.: (314) 577-5111; Fax: (314) 577-9595; E-mail: peter.raven@mobot.org

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INTRODUCTION

As the world's most populous country with the fastest-growing major economy, China is crucial in shaping the course toward global environmental sustainability. China's economic development has compressed into decades what took centuries in developed countries.[1] At the same time, environmental degradation has been greatly accelerated.[2,3] To reduce environmental impacts, China has chosen environmental protection as a national principle and sustainable development as a national strategy, and has implemented a series of environmental programs.[4] However, its environmental sustainability index is still ranked near the bottom among all the world's countries (see Table 1).[5]

The current global financial crisis has created new challenges and opportunities for China's environmental sustainability. The country's economic growth rate has fallen from ~10% per year during the past three decades to 9.1% in 2009,[6] but it still is very high compared with many other major countries experiencing slower or negative growth. Because of the financial downturn in those countries, China's exports have fallen, prompting China to take urgent and unprecedented actions. These actions include the creation of more domestic demand for consumption and implementation of

TABLE 1. China's current place in the world

Indicator	Place	Reference
Economic growth rate	First	(7)
Total gross domestic product	Second (after the United States)	(125)
Foreign direct investment	First	(117)
Foreign exchange reserve	First	(117)
Area of tree plantations	First	(37, 38, 40)
Production of steel	First	(7)
Production of cement	First	(7)
Production of aquacultural food	First	(7)
Production of television sets	First	(7)
Production of coal	First	(22)
Consumption of steel	First	(7, 8)
Consumption of fertilizers	First	(7, 8)
Consumption of coal	First	(22)
Consumption of petroleum	Second (after the United States)	(7)
Consumption of total energy	First	(123)
Population size	First	(118)
Number of households	First	(118)
CO_2 emissions	First	(119)
Environmental Sustainability Index	133th (out of 146)	(5)

massive infrastructure construction, which have significant implications for the environment.

The detailed literature on various issues related to China's environment is scattered, even for Chinese readers, and largely inaccessible to Western readers. Because China's environmental and economic conditions have been changing very rapidly (especially in the past several years), the vast majority of references cited in this paper are from 2007 through 2010. We offer a synthetic overview that has been largely lacking and may help both the Chinese government and the international community to develop effective and integrated responses. Specifically, we illustrate China's socioeconomic transformation; synthesize major environmental challenges, interrelationships, and impacts; and offer a systems approach to address environmental challenges.

SOCIOECONOMIC TRANSFORMATION

Over the past three decades, China has seen the world's most remarkable economic transformation (see Figure 1). The total gross domestic product (GDP) of China, which ranked near the bottom among the world's most populous nations three decades ago, has recently surpassed that of Japan. In GDP, China is now second to the United States, with a growth rate three times faster than the world average (see Table 1).[7] China has attracted the highest foreign direct investment of any nation for a number of years and, because of its export level, its foreign exchange reserve of >$2 trillion is by far the largest in the world (see Table 1). As the world's factory, China produces the largest quantity of steel, cement, food from aquaculture, television sets, and many other important industrial, agricultural, and household products; increases in production have been exponential. China also has become the largest

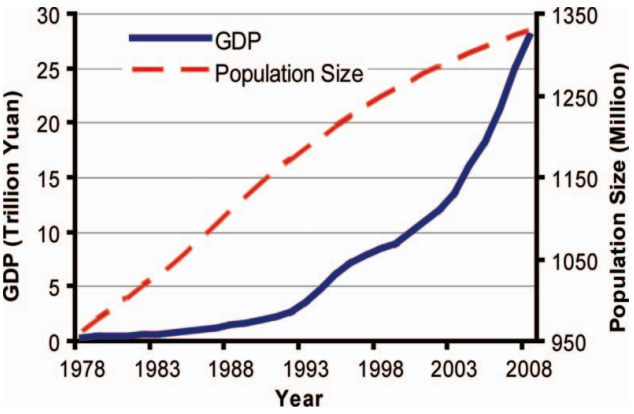

FIGURE 1. Growth of China's population size and gross domestic products.[121] (Figure is provided in color online.)

consumer of many products, including fertilizers and steel (see Table 1).[7,8] Even on a per capita basis, China's consumption of some products, such as eggs, has increased rapidly and is now close or equal to the consumption levels of developed nations.

China's unrivaled rate and quantity in economic growth partially result from its economic reform policy and from the largest population (see Table 1) and cheap labor force in the world. From 1978 to 2008, China's population increased by 359 million (see Figure 1), 55 million more than the total population in the United States in 2008, despite its "one child" policy which has averted over 300 million births by 2005.[9] The proportion of urban residents has more than tripled since the early 1950s, and ~21% of China's people now live in cities of >750,000 inhabitants, with 46% in all urban areas. Cities are expected to grow by 250 million people in the coming 25 years, an unprecedented shift that will create big challenges for every aspect of the urban systems, including health, education, housing, energy, food, and water.[10]

Dramatic social changes have also occurred in the past three decades. For example, Chinese now live in smaller households, so there will be 250 million more households by 2030 even without an increase in population.[7] The reduction in household size (number of people in a household) from 4.8 in 1975 to 3.1 in 2005 results from several factors. Traditional households with multiple generations under one roof are disappearing rapidly and many young people now establish new households before they are married. In the past, divorce was rare and strongly discouraged. Now divorce can be approved quickly and is increasingly widespread. In 2007, 1.9 million couples severed their ties and split into more and smaller households.[11] As the population ages and lives longer, there will continue to be increasing numbers of empty nesters without children.

These socioeconomic and demographic changes contribute to environmental challenges. For example, more households consume more resources and emit more pollutants,[124] and smaller households reduce the per capita efficiency of resource use and increase the per capita emission of pollutants.[12] Rapid industrialization has led to enormous environmental damage in many regions.[8] High agricultural productivity has been bought at the expense of high inputs of fertilizers and pesticides,[13] which in turn have led to widespread pollution. The government and general public in China have become increasingly aware of environmental problems and have been taking many measures to protect the environment. However, despite these efforts, production, transportation, and consumption of raw materials and products profoundly pollute the environment and lead to a variety of environmental challenges.

ENVIRONMENTAL CHALLENGES

In concert with China's unprecedented economic growth,[14] its environmental problems are growing as rapidly as anywhere on the planet. Many old problems have not been solved, and new problems are emerging one after another.[4] Environmental challenges have spread far beyond the cities.[15] Rural environmental problems are increasingly acute, with increased quantities and sources of domestic and industrial pollution.[16] China's total ecological footprint has quadrupled in the last 40 years, with the country now demanding more from the planet than any other nation except the United States,[17] although ecological footprint per capita in China is much lower than that of developed countries. In this section, we highlight a number of major environmental challenges.

Climate Change

In the past 50 years, temperature has increased 0.26 and 0.18 degrees per decade in eastern and western China, respectively. The average temperature in China is projected to rise 1.3–2.1°C by 2020 and 2.3–3.3°C by 2050.[18] Glaciers have shrunk, and sea level has risen 0.1–0.25 cm/year.[19]

Climate change largely results from the accumulation of some 16 kinds of greenhouse gases in the atmosphere, with CO_2 being the principal one of anthropogenic origin. China now emits more CO_2 per year than any other country (see Table 1), with an increase of 7% in 2007 (see Figure 2).[20,21] Although China's total CO_2 emissions have exceeded those of the United States, per capita emissions are only 20–25% of the U.S. levels. Unless drastic steps are taken, China's emissions will continue growing substantially for years to come due to continued rise in resource use by the increasing number of households as well as the expanding industry and transportation.

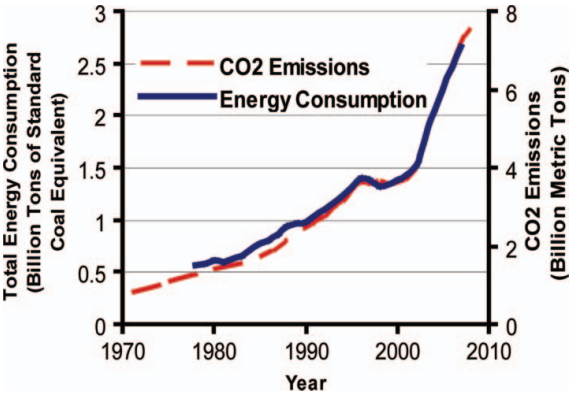

FIGURE 2. Changes in China's energy use and CO_2 emissions.[20,21] (Figure is provided in color online.)

Energy Consumption and Development

Fast economic growth has turned China into the world's largest energy consumer (see Table 1), with its total consumption level having increased more than fourfold since 1980 (see Figure 2). China leads the world in production and consumption of coal (~25% of the world's total),[22] which is plentiful but the dirtiest energy in terms of pollution. Coal is still China's dominant energy source, although coal has declined from producing >90% of China's total energy in the 1950s to ~70% in recent years. In addition, China has replaced Japan from 2003 onward as the second-largest consumer of petroleum after the United States (see Table 1).

Renewable energy (e.g., wind, solar, biomass, nuclear, ocean, hydropower) in China presently accounts for <7% of the total energy consumed. It is projected that the contribution from renewable energy will increase to 10% by 2010 and 16% by 2016.[23] Hydropower has risen in importance partly because of the 18.2-gigawatt Three Gorges Dam project. China has also been developing solar and wind power as potentially significant energy sources. The total contribution of natural gas has risen from almost none to ~3% in 2006 because of increased production and imports. The first 3,800-km pipeline for transporting natural gas was completed in 2005, and a 9,102-km pipeline is currently being constructed from Turkmenistan and China's Xinjiang Uygur Autonomous Region to the Yangtze and Pearl river deltas with an investment of 142.2 billion yuan[24] (1 U.S. dollar = 6.78 yuan, as of July 2010). Nuclear power is being developed rapidly, and is expected to contribute 5% of China's energy needs by 2020. Despite an increasing proportion of renewable energy and a declining proportion of non-renewable energy, the total amount of non-renewable energy use is still increasing and will continue to increase,[25] thus creating more environmental challenges.

Air Pollution

China's extraordinary efforts to decrease air pollution in and around Beijing during the 2008 Olympics highlighted the problems with most of China's cities. Although discharge of SO_2 in 2008 was reduced by 5.95% from the 2007 level, among the 519 cities that reported air-quality data, only 21 (4.0%) reached the government's highest standard.[16] More than a quarter of China's area is currently affected by acid precipitation from the oxidation of SO_2 (see Table 2).

A major source of pollutants in China's modern cities is the transportation sector, where vehicles and transportation networks have grown explosively. As the world's third-largest vehicle manufacturing nation, China has promoted car production as one of its pillar industries and economic engines. During the past decade, China's vehicle fleet has tripled to 45 million.

TABLE 2. Air pollution, water pollution, and water shortages in China

Indicator	Degree of impact	Reference
Number of cities reaching the highest air standard	21 of 519	(16)
Percent of cities reaching the highest air standard	4.0%	(16)
Percentage of area affected by acid rain	>25%	(7)
Number of cities with water shortages	400 of 669	(29)
Percent of cities with water shortages	59.8%	(29)
Percent of lakes/reservoirs suffering from eutrophication	46.2%	(16)

In January 2009, more cars were sold in China than in the United States for the first time during a single month. China has great potential for auto production and consumption, because there are only 30 automobiles per 1000 persons, compared to 600 automobiles per 1000 persons in the United States.

Water Scarcity and Pollution

Water resources in China are in short supply, severely polluted, and often wasted.[26–28] Average per capita water is only one-quarter of the world average (see Table 3). Approximately 400 of China's 669 cities are faced with water shortages, with >100 seriously affected. This shortage becomes more complex when considering the huge differences in annual rainfall among different regions, ranging from <100 mm to >2,000 mm per year.[29] In the North China Plain, which produces ~40% of China's food, the groundwater level is dropping rapidly, and is hundreds of meters below ground in some areas.[28]

Increasing amounts of wastewater discharged exacerbate the problem of water scarcity (see Figure 3).[7] Many projects and factories with high water consumption and heavy pollution are located in regions with low environmental carrying capacity and high fragility. Nearly half (46.2%) of the 26 lakes (reservoirs) monitored across China suffer from eutrophication (see Table 2).[16] Nonpoint agricultural pollution in China is intense, with the country being the world's largest consumer of chemical fertilizers, the largest

TABLE 3. Per capita resource in China compared to the world average

Resource	Proportion of the world average	Reference
Forest area	1/6	(7)
Freshwater amount	1/4	(29)
Grassland area	<1/2	(7)
Cultivated land area	<1/2	(7)
Amount of 45 major minerals	<1/2	(76)

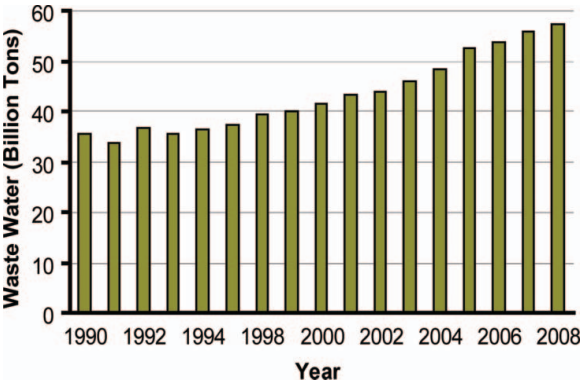

FIGURE 3. Dynamics of China's waste water discharged over time.[121] (Figure is provided in color online.)

producer and consumer of pesticides,[13] and now the world's leading livestock producer. Only a small portion of urban and industrial wastewater is treated before being released back to the environment (10% in Shanghai, and virtually no treatment for >3/4 of the Chinese population).[30] A growing proportion of China's surface water is becoming too polluted for irrigation, much less for human consumption. Besides freshwater, China's oceans and coastal areas are also increasingly polluted, both from the land and from marine activities.[30,31] In 2004, the area of Chinese coastal water below the government's clean water standard reached 169,000 km^2.[32]

Furthermore, water is being inefficiently used: GDP per unit of water in China is only one-third of the world average. Since 2005, water consumption per unit GDP has been gradually reducing, and China has been making progress toward the central government's goal of reducing water consumption per unit GDP by 20% during 2006–2010,[9] thanks to the partial changes in the development model and industry structure. However, China has a long way to go in altering its industry structure and development model to increase efficiency.

Land Conversion and Degradation

China has diverse landforms, including mountains, plateaus, basins, plains, and hills, which account for 33.33, 26.04, 18.79, 11.98, and 9.90%, respectively, of its topography.[33] Its land cover and land use are very heterogeneous and have undergone marked changes.[34] China's limited cultivatable land (<0.1 ha/person, hardly half of the world's average; see Table 3) has been increasingly reduced and degraded. By the end of 2008, only 122 million ha of cropland were left, very close to the government's "red line" for food security of 120 million ha.[35] In the same period of time, land area affected by soil erosion spread to 370 million ha, ~38% of the country.[1] In the past 50 years, 3.3 million ha of cropland have been lost due to soil erosion

alone. Soil erosion also causes heavy loss in nutrients such as nitrogen.[8] Industrial waste and domestic trash have occupied or damaged ~10 million ha of cropland.[7] From 1996 to 2008, 8.4 million ha of cropland were lost due to construction and other causes (e.g., housing, roads, and highways). In 2008 alone, construction took 313,333 ha of agricultural land. In an effort to increase forest cover and grasslands, the Grain-to-Green Program had converted ~9 million ha of cropland on steep slopes by the end of 2006.[36]

There is only 0.1 ha of forest per person in China (roughly one-sixth of the world average; see Table 3), and percent forest cover is a little over half of the world average (30%). Thanks to conservation programs such as Natural Forest Conservation and Grain-to-Green,[36] China's forest cover has increased from 12% in 1981 to more than 20% in 2008,[37–39] although much of the added forest is composed of planted exotic species or single-species tree plantations. (China has the largest area of tree plantations in the world. In fact, China is ranked first in the world in terms of tree plantation areas, a total of 62 million ha by 2008.[37,38,40])

China's grasslands are less than half of the world average per person (see Table 3). Since the early 1980s, grasslands have been shrinking at ~1.5 million ha/year.[7] Furthermore, ~90% of China's grasslands have degraded by the invasion of weeds and poisonous plants, overgrazing, and human activities.[1]

With the disappearance of ~30% of China's natural wetlands between 1990 and 2000, they now cover only 3.8% (36.2 million ha) of China's territory,[41] compared to the global level of 6.0%.[7] The function of remaining wetlands has declined in terms of flood mitigation and water storage capacity.[1,7]

Biodiversity Loss and Deterioration

China is one of the most biodiverse countries in the world, probably exceeded only by Brazil, Colombia, and Indonesia. It has 16 major biomes based on plant functional types.[42] China is home to the richest assemblage of biodiversity in the temperate northern hemisphere, with at least 2,340 species of terrestrial vertebrate species (of a world total of about 25,000 named species) and ~31,500 known species of vascular plants (world total: >350,000). With the total number of eukaryotic species globally estimated at >12 million,[43] the ultimate total for China is likely to be approximately one million species, 8–9% of the total if the proportional representation of less well-known groups is similar to that for terrestrial vertebrates and vascular plants. Of these, <150,000 have actually been recorded for the country.

Considering habitat destruction, global climate change, invasive species, and selective hunting and gathering, it is likely that more than half of the species in the world will disappear permanently during the 21st century. There seems to be no reason to think that the situation will be any better in China, where more than half of the species known are found only in China.[44]

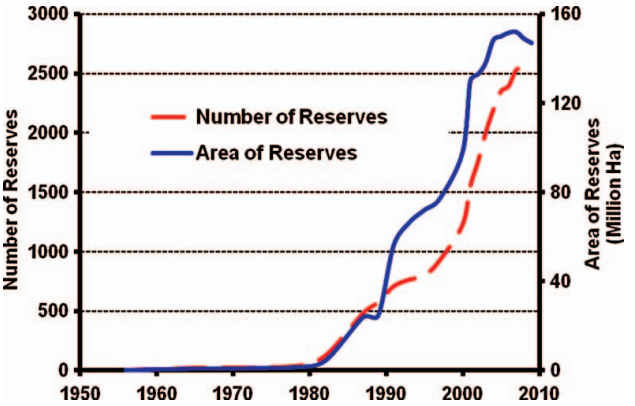

FIGURE 4. Dynamics of China's nature reserves (area and total number).[7,121,126] (Figure is provided in color online.)

The loss of such a high proportion of global biodiversity in a single country will be a tragedy not only for China but for the world at large, and whatever steps are possible should be taken to alleviate the problem.

China's biodiversity conservation has achieved mixed results in the context of the 2010 biodiversity target set by the United Nations' Convention on Biological Conservation.[45] For example, it has been building an impressive system of nature reserves, reaching 2,541 in 2009 and occupying ~1.47 million km^2 (~15.3% of China's territory) (see Figure 4). More than 60 nature reserves have been established to protect giant pandas alone. Unfortunately, the congruence of areas rich in endemic biodiversity and nature reserves is often not close.[46] Furthermore, many reserves are listed on paper and have insufficient funding and ineffective management.[12] Some reserves are now empty because target wildlife species such as tigers no longer exist in the areas that were originally established to conserve them.[47] Compared to the number of endangered wild giant pandas (approximately 1,590),[48] the number of remaining wild tigers in China is even smaller due to habitat loss and poaching: only about 50 wild tigers (i.e., roughly 20 Bengal tigers in Tibet, 20 Siberian tigers in the northeast, and 10 Indochinese tigers in the southwest).[49]

The changes in available habitats that are accompanying global climate change will drive many species to extinction; such changes render conservation strategies much more difficult than they would be otherwise. Some species are being preserved in botanical gardens and seed banks, tissue culture, or captivity, and the cooperative assembly of a national seed bank at the Institute of Botany of the Chinese Academy of Sciences in Kunming should be fully supported.

Interrelationships among Environmental Challenges

Environmental challenges are usually addressed separately but, in reality, are closely interrelated. Efforts to reduce one challenge may exacerbate or minimize other challenges. For example, a network of canals (South-North Water Diversion Project) is being built to move water from the wetter south >1,000 km north to thirsty Beijing and the North China Plain; by 2050, these canals may supply ~44.8 billion m^3 of water per year, equal to the entire annual discharge of the Yellow River. This 500 billion yuan attempt to tame nature consumes a huge amount of energy to pump, move, clean, treat, distribute, and use the water. The project also consumes agricultural land, converts natural land, spreads pollution, causes biodiversity loss, reduces ecosystem services, and generates CO_2. Furthermore, it is displacing >440,000 people and has cascading environmental consequences as a result of the displacement.[50,51]

The energy intensity of producing and supplying water in China dropped ~30% between 1997 and 2004. However, energy consumption will rise as China expands water treatment capacity and hydraulic infrastructure.[52] Treating other pollutants also consumes energy.

In 2007, China announced a moratorium on the use of food crops such as maize for bioenergy and is pursuing the use of other plant materials for this purpose. Such an approach has the potential for alleviating the use of carbon-based fossil fuels, but may run the risk of reducing agricultural land for food. A global effort to replace gasoline with biofuels is ongoing.[53] However, a large amount of water is needed to grow bioenergy crops; water footprints range from 1,400 to 20,000 L of water per L of biofuel, depending on crop types. Thus, water used for biofuel cannot be used for other purposes such as growing food crops.[54] The ultimate place of biofuels in the world economy remains to be seen as newer methods for producing and utilizing them are developed.

Climate change threatens the future of water supplies in many parts of the world and is causing both mountain glaciers and ice sheets to melt and severe droughts in many regions. These effects are being seen in China, and climate change in conjunction with air pollution, land conversion, and high energy use will make the situation worse and cause biodiversity loss and degradation.

To expand land area, China has also been filling the sea. In 2009, China planned to create 150 km^2 of land in coastal regions, an increase of ~40 km^2 from 2008.[55] This encroachment on the sea may have unexpected consequences, particularly in the face of the sea-level rise that accompanies global warming.

IMPACTS OF ENVIRONMENTAL WOES ON HUMAN WELL-BEING IN CHINA AND BEYOND

Environmental challenges affect every aspect of human well-being in China and other parts of the world. In this section, we highlight a few health and socioeconomic impacts of environmental woes.

Human Health

Life expectancy has increased significantly around the world, including in China, thanks to medical improvement and health care. However, the health effects of pollution are alarming. One-third of China's 1.3 billion people breathe polluted air (see Table 4), which increases mortality in vulnerable people, especially children and elders. The number of deaths caused by air pollution has reached 650,000–700,000 per year,[56,57] many of them related to the small (<150 μm) particles emitted by coal-burning plants.

Cancer has greatly increased as a major cause of deaths in China. Incidents of lung cancer have increased by 465% during the past 30 years. Among the cancer-caused deaths, 80% are related to chemicals in the environment. In 2006, two-thirds of China's 2 million deaths from cancer were related to environmental pollution.[58] More than 100 "cancer villages" have been reported, where cancers have caused an exceedingly large number of deaths in a given population, including children.

The quality of drinking water for more than 300 million rural people is below the government standard (see Table 4).[59] Hundreds of millions of Chinese are drinking water contaminated with inorganic pollutants such as arsenic, excessive amounts of fluoride, and many other toxins.[60] The health problems associated with contaminated drinking water are extensive in China.[28]

The loss of biodiversity also has important implications for human health. Most people in rural China still depend on traditional herbal medicine, which is widespread in urban areas as well. In 2005, sales of herbal medicine products reached $14 billion.[61] With several thousand species of medicinal plants regularly used in China, preserving them, understanding their diversity, and finding ways to bring them productively into cultivation will take

TABLE 4. Number of people affected by environmental problems in China

Environmental problems	Number of people (million) affected	Reference
Bad air in urban areas	430	(120)
Poor drinking water in rural areas	300	(59)
Desertification	400	(64)

on increasing importance. Sweet Wormwood (*Artemisia annua*), a Chinese herbal medicine widely used for the prevention and treatment of malaria, illustrates the global importance of some of these plants in China.

Socioeconomic Costs

Although economic growth has elevated income and provided better clothing, housing, and diets for millions of Chinese, the environmental problems have now become so severe that they are not only negatively impacting human health but also are causing social unrest and limiting economic growth. Social instability is marked by widespread public demonstrations regarding environmental problems. In 2007 alone, 60,000 pollution-related demonstrations and protests were officially reported in China. The cost of environmental damage has been estimated at 8–13% of the GDP, roughly equivalent to the stated economic growth rate over the past three decades.[62,63] Almost 400 million people are under the threat of desertification (see Table 4), and direct economic loss from desertification is more than 50 billion yuan/year.[64] China's economic boom has clearly accelerated biological invasions by alien pests and diseases.[65] In this connection, it is estimated that at least 283 invasive species have caused direct annual economic damage of more than 200 billion yuan,[66] with invasive species such as water hyacinth (*Eichornia crassipes*) adversely affecting economic sectors ranging from electricity generation to transportation.[67]

The consequences of increasing global warming include flooding, wildfires, droughts, lethal heat waves, pest outbreaks, coral bleaching, more powerful typhoons, shifts in the natural ranges of plants and animals, and the spread northward of tropical pathogens.[15] For China, changes in monsoon patterns lead to the intensification of floods and droughts. The dwindling Himalayan icecap is already limiting dry-season flow in the major river basins and, with further temperature increases, will have truly drastic effects on China and other countries that depend on water from this source. At the same time, a rise of sea level by 1 m, the minimum rise projected for the remainder of the 21st century, would inundate 92,000 km^2 of land in China's three major industrial centers: the Gulf of Bohai region with the Beijing-Tainjin axis, the Yangtze River delta radiating inland from Shanghai, and the Pearl River delta encompassing Hong Kong and Guangzhou.[68]

Agricultural productivity is affected by environmental changes in many ways. The output of major crops such as wheat, rice, and maize may fall by up to 37% in the second half of this century if no effective measures are taken to address the problem of climate change over the coming decades.[18] In the past 10 years, cropland under droughts reached 20 million ha annually, of which 6.7 million ha experienced disasters.[69] Early in 2009, the unusually severe drought (once every half century) in north China affected 10.7 million ha of wheat cropland. In addition, almost 4.4 million people and 2.1 million

livestock lacked drinking water. In an attempt to ameliorate the losses related to this drought, the central government allocated subsidies of 86.7 billion yuan.[70]

Overpumping of underground water resources has led to serious drops in water tables in many parts of China. At least 96 cities and regions in China have experienced surface subsidence of 10–56 mm/year, causing severe damage, such as a reduction in agricultural productivity and destruction of buildings. With increasing water shortage and pollution, fishery resources have been significantly reduced and degraded.[32]

INCREASING LINKAGES BETWEEN CHINA AND THE REST OF THE WORLD

Globalization is increasingly connecting China with the rest of the world (see Figure 5). The country's economic boom has benefitted billions of people around the world by providing cheap products, but many outdated and polluting technologies from other countries have been imported to China and used to produce many of these products. As the products are exported, China's resources are consumed and pollutants are left behind.[7] Production of exported items was responsible for almost one-third of the CO_2 generated in 2005 in China.[71] China's terrestrial ecosystems (e.g., forests) assimilated approximately one-third of its cumulated fossil carbon emissions during the 1980s and 1990s.[72] On the other hand, some of the environmental pollution related to the economic boom reaches far beyond China's border. In addition to CO_2 emissions generated during production, many pollutants such as soot regularly reach Japan and South Korea and at times even North America. Pollutants in upstream rivers, such as the Songhua River of north China, also affect oceans and downstream areas in other countries.

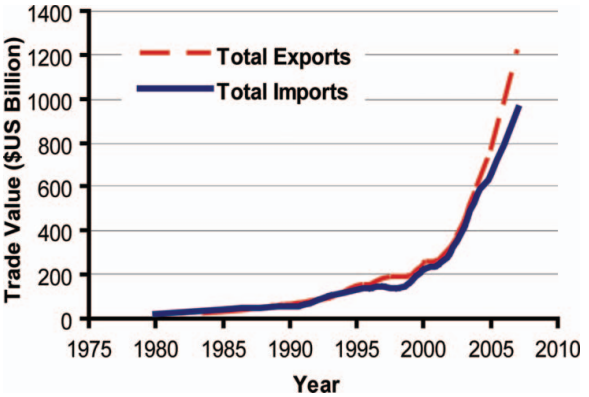

FIGURE 5. Annual amounts of China's export and import over time.[121] (Figure is provided in color online.)

China's grassland degradation not only reduces food production in China, but also affects the quality of water flows through the country to major rivers in all of southeast Asia.[7,73] Although it was a positive step for China to discontinue harvesting its natural forests, the expanding demand for wood in China is leading to the destruction of forests elsewhere in the world, especially in southeast Asia.[74] Because China's mineral resources are relatively scarce on a world scale[12,75] and the per capita amount of 45 major minerals is <50% of the world average[76] (see Table 3), China has increased extraction of minerals in other regions such as Africa and Australia, which also affects international relationships and the environment of the nations exporting to China.[58,77] A large number of people in China still have a strong predilection for exotic animal parts, such as tiger bones,[78] which motivates the poaching of endangered wildlife and international smuggling and illegal trade of animal parts.[79] As China's wealth increases, the consumption of wildlife parts and its international impact will likely increase unless more serious action is taken.

SYSTEMS INTEGRATION FOR ENVIRONMENTAL SUSTAINABILITY

China has taken many actions regarding environmental protection and sustainable development,[80] such as participation in the development of the historical document *Our Common Future,*[81] the release of China's Agenda 21,[82] the implementation of a scientific development concept, development and use of more renewable energy, reduction in emissions of pollutants per unit GDP, and commitment to low-carbon economic development.[83,84] Environmental programs such as the Natural Forest Conservation Program and the Grain-to-Green Program, the protection and restoration of natural wetlands,[85] pollution control, and the establishment and enforcement of environmental standards are laudable and need to continue. These and many other actions are important, but they have not stemmed the overall trend of environmental degradation. In this section, we outline a systems approach that integrates major, important issues for environmental sustainability.

Coupling Human and Natural Systems

Understanding human–nature relationships is a foundation for eliminating environmental woes and achieving environmental sustainability. Although humans and natural systems were often regarded as a single entity in ancient China, it has widely been accepted that humans can and should conquer nature.[86] To achieve sustainability, human–nature harmony, and social harmony that the Chinese government has begun to promote,[86] it is essential to explicitly treat China as a series of coupled human and natural systems (CHANS), in which humans and natural systems interact.[87,88] Coupling human

and natural systems can help people to appreciate the reciprocal essence of human–nature interactions and thus encourage them to take actions that are more friendly to the environment. If such actions become fundamental for us all, essential ecosystem services will continue to be supplied.

The CHANS perspective also enhances the understanding of the complexity of relationships between humans and nature, among humans, and among various components of nature. China has a diverse set of CHANS and is part of the global CHANS. Many interactions in CHANS are nonlinear and heterogeneous (e.g., variations across space, time, and organizational units). Some consequences (e.g., impacts of environmental pollution on human health) might not be observed for a long time (time lag) and may have long-lasting impacts (legacy effects).

Understanding CHANS and addressing societal challenges require the integration of social sciences with natural sciences and technology.[89] Recently, the Chinese Academy of Sciences released the 2050 Science and Technology Blueprint,[90] which outlines ambitious goals for China's scientific development and technological innovation over the next four decades. In contrast, and as in the rest of the world, social sciences in China lag behind and receive much less attention and support, even though they are of fundamental importance in increasing the effectiveness and efficiency of resource use and conservation investment. For example, saving energy depends on not only innovative technology, but also changes in human attitudes, intentions, and behaviors. Also, understanding social norms can help enhance efficiency of conservation investments.[91] For instance, when farmers enroll in conservation programs such as the Grain-to-Green Program, their neighbors are likely to follow suit. To achieve the best results, social and natural sciences need to be fully developed and applied together to the solution of environmental problems.

Studies on CHANS have increased around the world, as illustrated by the International Network of Research on Coupled Human and Natural Systems (CHANS-Net, www.chans-net.org). Despite these efforts, more China-specific CHANS research is needed, as it will have more direct relevance to China's sustainable management. For example, expanding China's long-term ecological research stations into CHANS research stations would lead to many insightful discoveries.

Turning Crises into Opportunities

Although crises like the recent global financial slump affect human well-being, they can be opportunities for sustainable development. Now it is the time to transform China's economic development model by restructuring polluting sectors and phasing out backward factories. Countries such as the United States, Britain, and South Korea are already using this economic slowdown to retool and reorient their economies.[92] Top Chinese leaders

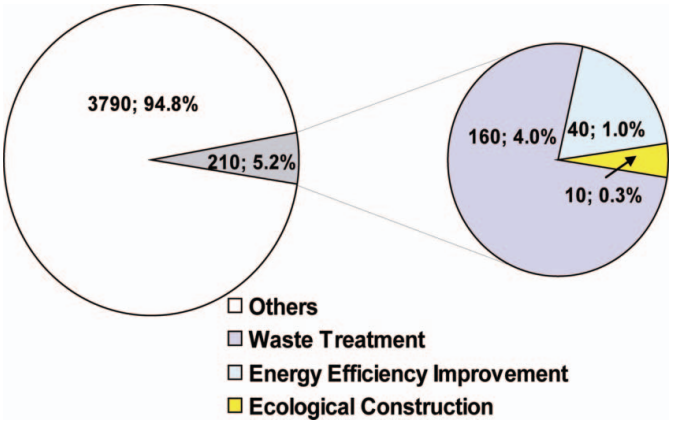

FIGURE 6. Distribution of China's stimulus money (absolute amount in billion yuan; percentage).[122] (Figure is provided in color online.)

have also stated their intention to adjust economic structure and promote environmental protection amid the current financial crisis, which certainly has made evident the need for comprehensive interrelationships between nations to achieve effective responses.

China and many other nations have been taking action to counteract the current financial crisis. China's central government has offered the second-largest stimulus package (4 trillion yuan [~$585 billion]) in the world, following the United States. Local governments and companies are expected to pool an additional several trillion U.S. dollars on new development projects. A small proportion (5.3%, or 210 billion yuan) of the central government's stimulus money has been allocated for environmental protection (see Figure 6). China has also taken new initiatives on green technologies and renewable energy. In 2007, the Renewable Energy Law was passed. In 2008, when investment in renewable energy by developed countries dropped, China's investment, the highest in Asia, grew 18% over 2007 and reached $15.6 billion, accounting for ~10% of the global investment in this area.[93]

Conversely, Chinese banks have lent money to many polluting factories quickly. In the hurry to spend the stimulus money, a new "green-light passage" policy has been adopted by the Ministry of Environmental Protection (MEP) and local environmental protection agencies since November of 2008. This new policy does not follow the usual procedures and receives no public input. During a three-day period in November 2008, for example, MEP reviewed 93 new development plans worth >260 billion yuan.[94] From November 2008 to May 2009, MEP reviewed 365 big projects with a total investment of 1,442.8 billion yuan, of which ~92% (336 projects) were approved and only 8% (29 projects worth 146.7 billion yuan) were rejected or deferred.[95]

This new round of quick development is likely to produce even more pollution. Before the financial crisis, environmental performance was becoming a criterion for evaluating and selecting government officials, but the financial crisis has brought back the dominance of GDP growth in official thinking. Some regions, such as Guangdong Province in southern China, had begun to bring in greener, high-tech enterprises and transfer energy-intensive industries to other regions particularly in western China, but the provincial government has had to slow the process to provide jobs to millions of rural-to-urban migrants.[96]

For the medium and long term, it would be better for China and other nations to take advantage of the economic slowdown and accelerate the process toward low-emission industries. Clean production and a circular economy are examples of sustainable development.[76,97] Without a bold shift in the economic development model, it is possible that economic recessions will occur again because investment will increase demand for raw materials, which will increase production, and excess production can lead to recession. With the right approach, emerging industries such as bioenergy and solar energy could become bright new areas of future development and create more "green-collar" jobs.[98,99]

Becoming an International Leader

Since 1972, when China's delegation attended the first United Nations Conference on the Human Environment,[100] China has participated in many international efforts on environmental protection and sustainable development. Given its increasing impact as an economic powerhouse and a major environmental polluter, China is well positioned to take a more active leadership role in helping to steer the world to a sustainable future.

Ample reasons exist for China to take bold steps to implement sustainable development, such as curtailing global warming. As the world's largest CO_2 emitter, China may benefit from cutting CO_2 emissions just as it has benefitted from joining the World Trade Organization. Although China made compromises to reduce certain trade and investment barriers in joining the organization, the benefits have far outweighed the compromises. Similarly, there are certainly short-term economic costs to reduce CO_2 emissions, but long-term gains will be higher than the short-term losses.

China's per capita and historical total contributions to CO_2 emissions are small compared to developed countries, but the impact of climate change on China is huge because it has the world's largest population, with several hundred million particularly vulnerable people living in environmentally fragile areas and/or still under the poverty line. Working together with developed countries such as the United States (the largest CO_2 emitter among developed countries) and other developing countries such as India (the second-largest

CO_2 emitter among developing countries), China can help break the deadlock now hampering the development of a comprehensive, global climate agreement. Partnerships in the development of key technologies such as electric cars and batteries could do much to jump start the search for common solutions.[101,102] Whereas developed countries need to cut their emissions significantly and provide poor countries with technical and financial support, rapidly developing countries such as China, India, and Brazil need to share part of the costs.[103]

CO_2 emissions must ultimately be reduced in absolute amounts not just relative amounts (on a per GDP basis).[104] China has been implementing impressive measures to reduce relative CO_2 emissions and has promised to develop a low-carbon economy. It is developing energy policy faster than the United States, including an enhancement of its attempts to increase energy efficiency, and is mounting efforts to become a world leader in electric transportation and solar energy.[105]

With a rapidly growing number of scientists and engineers, China can make important contributions to the achievement of global sustainability.[106] For instance, there is a strong need to create "genetically engineered carbon-eating trees"[107] and perhaps other types of plants that store as much carbon as possible. Land plants absorb a net 60 billion tons of carbon annually, with marine plants absorbing a similar amount. Increasing the total terrestrial absorption capacity by just 10% would be sufficient to absorb ~80% of current fossil fuel emissions. It is likely that Chinese scientists can play a leadership role in this globally important effort, judging by the successes they have achieved in agriculture.[108]

Coordinating Activities across Scales

Stronger efforts are necessary to deal with the many interlocking problems that beset China across different spatial, temporal, and organizational scales. A fundamental challenge in achieving sustainability is the coordinating of short-term and long-term activities. It is necessary to move away from short-term solutions to all problems. Because China is already plagued by overcapacity in some industries (e.g., steel and petrochemicals), its enormous stimulus funds may build excess capacity that may not be fully used, which may generate both financial and environmental waste.[109]

More concerted efforts are needed to resolve many environmental conflicts at smaller spatial scales, such as upstream vs. downstream, urban vs. rural areas, and coastal vs. island regions. Paths to sustainability will vary in different regions, because there are huge regional differences in geographic, environmental, climatic, and socioeconomic conditions. For example, large-scale planting of trees should not take place in unsuitable arid areas; only 15% of trees planted in arid and semiarid northern China have survived.[110] Such efforts will continue to fail, and good intentions for ecosystem restoration will lead to more serious environmental degradation. Similarly, opportunities for

incremental improvement, leapfrogging, or radical innovation in technology exist at different stages of development in different parts of the country.[104]

Environmental and economic activities at all organizational levels should be coordinated and strengthened.[7] The current Ministry of Environmental Protection is more powerful than its predecessors but still has limited powers for achieving effective coordination. As the difficulty in dealing with pollution in Lake Tai clearly showed, coordination between ministries and local governments in dealing with environmental problems presents a serious challenge that affects every aspect of Chinese life.

Some sustainability actions may have negative effects on conservation. Thus, tradeoffs need to be made. For instance, wind turbines kill large numbers of bats each year. To reduce mortality, some nocturnal spin time could be sacrificed.[111]

Enhancing Environmental Policies and Management

China has established more than 100 environmental laws and policies, but each focuses on a specific aspect of the environment, often ignoring the interactive effects among different components of the environment. For example, there are separate laws and policies regarding protection of water, air, and land. Furthermore, implementation and timely revisions of existing laws and policies are often lacking. Two exceptions are the Natural Forest Conservation and Grain-to-Green programs. Although there is room for improvement, overall they are very successful,[36] probably because the central government provides the vast majority of funding to implement them. In contrast, implementation of programs for which the central government has provided little or insufficient funding is largely not enforced. Thus, a substantial portion of China's foreign exchange reserve (the world's largest) should be used to enhance the effectiveness of environmental programs, offset China's environmental deficit, and prepare the country for an even more prosperous future. Coordination with individual provinces and localities, as well as with the growing private sector, is of profound importance in achieving a healthy, sustainable environment.

Despite widespread reluctance to do so, every country including China must develop economic metrics that take into account the environmental costs associated with its development. Development of the Chinese "green GDP" in 2004[112] represented a positive step in this direction, and, in view of the extent of environmental problems that is now so evident, would logically be reinstated.[113]

During the past three decades, China has been transitioning from a planned economy to a market economy, and more market mechanisms are needed to change people's behaviors. For instance, water has long been heavily subsidized in China, as it is in many countries; more realistic pricing would be an important stimulus for its more efficient use.[27] Although the

average water price in China increased over time, it is still well below the global market price. As water prices increase, the government should still provide subsidies to people who cannot afford their basic water needs.

Environmental management such as water management needs to be greatly strengthened to be effective. The adoption of drip technology for irrigation can lead to dramatic increases in efficiency, especially in dry areas. Growing crops that require less water would be a useful part of an overall strategy. Largely because of the increased consumption of animal products for food in recent years, the per capita requirement for water used in food production in China has tripled since 1961, although it is still lower than water use in many developed countries.[114] The demand is still rising rapidly and may increasingly depend on "virtual water" (water supplies in other countries that are in effect transferred to China through food importation).

Engaging the Public

Achieving environmental sustainability in China and elsewhere requires active participation of the public in all related activities, such as disseminating sustainability information, monitoring and reporting environmental damage, enforcing environmental laws and policies, increasing resource use efficiency, and reducing environmental pollution. A crucial step is to increase public awareness of the importance of sustainability and the functioning of coupled human and natural systems. Partnerships among government agencies, nongovernment organizations, and schools should be enhanced. Popular books on sustainability should be widely available, and sustainability-themed advertisements should appear regularly in newspapers and on the Internet and radio and television stations.

Sustainability themes should be emphasized from the first year in school through the university level, and teachers should be trained and given the means to teach such courses effectively. Improved standards for education in rural areas and expediting the access of rural students to high-quality schools would certainly assist in the attainment of sustainability. Education in schools and for the general public will lead to the formation of a widespread desire for promoting sustainability throughout the country. For instance, education programs such as "Saving Water across China" are useful to increase awareness of the public to save water and promote changes in industry structure and coordination among resources, environment, and socioeconomic development.[115]

In addition to traditional settings (e.g., schools and parks), households should serve as laboratories for sustainability education. William Clark at Harvard University asks his students to estimate energy use in their households, report their findings in the classroom and to their family, and discuss where and how energy can be saved. This approach can be extended to

other universities, K–12 schools, and the general public. If every household can evaluate patterns of household resource use and improve resource use efficiency, the outcome would be remarkable, because residential energy use accounts for 37% of China's total energy consumption.[116] Unlike many other settings, households are familiar to everyone; parents and children teach each other. Education at the household level can lead to many immediate sustainability actions, such as choosing green household products, reducing energy use, increasing recycling, and generating cascading effects beyond households (e.g., determining the types of products that factories produce).

CONCLUDING REMARKS

Achieving environmental sustainability is the most daunting challenge in human history. Considering China's goal to quadruple 2000's per capita GDP by 2020, environmental sustainability will be difficult to attain without a systems approach and bold action. It is our belief and hope that China will play an elevated role in the world's transition to sustainability, because it is endowed with growing sustainability awareness, technical capacity, improving governance, and rising economic powers. In the meantime, it is necessary for developed countries to continue providing China more green technology and assist China in the development of technology for high efficiency and less pollution. We are cautiously optimistic that the world will revolutionize sustainability ideas and technologies as it revolutionized, for example, communications. Cooperation and trust among all nations, especially giants like China and the United States, are particularly important to a sustainable world.

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