The Environmental Reach of Asia

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Abstract

More than 10,000 years ago, humans began an experiment on the environmental consequences of resource use. The environmental changes were at first local. By 6000 years ago, the consequences had begun to be manifested at the regional and global scales. At the beginning of the experiment, Asia played a founding role. Populations were centered there, and agriculture and associated land-use change began there. Now Asia, with 60% of the world's population, is rapidly growing in terms of both population and economic development. Over the next few decades, population growth will slow, but economic growth will continue, resulting in large-scale losses of S, C, and N compounds to the atmosphere. A global challenge is to implement growth scenarios that, on one hand, will not limit the ability of the Asian population to attain a higher standard of living, but, on the other hand, will not result in a continued degradation of the environments within Asia as well as downwind and downstream of Asia.

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INTRODUCTION

More than 10,000 years ago, humans began an experiment on the environmental consequences of resource use that continues to this day. The development of agriculture in the Fertile Crescent (the northern part of the Syrian Desert and extending from the Nile Valley to the Tigris River) and in northern China, and its spread to other regions of the world in the following millennia, resulted in landscape changes that increased chemical flux of species of several elements, including S, N, and C, to the environment, especially to the atmosphere. The environmental changes were at first local, but by 6000 years ago, their beginnings of regional- and global-scale manifestation occurred (1).

The changes were due to both direct and indirect drivers. As delineated by the recently completed Millennium Ecosystem Assessment, direct drivers were habitat change, climate change, invasive species, overexploitation, and chemical release. Indirect drivers included population change, economic change, technological change, and sociopolitical and cultural factors.

At the beginning of the experiment, Asia played a founding role. Populations were centered there, and agriculture and associated land-use change began there. Over time, Asia has continued to be a major factor in the experiment. More than half of the world's population lives in Asia; thus agricultural drivers of change are also centered there. In the twentieth century, other regions of the world became the dominant force in other global-scale changes (e.g., fossil fuel combustion), but their dominance was temporary. Asia is projected over the next few decades to be once again the dominant force in alteration of the global environment.

It is thus fitting that this first integrated regional study is about Asia. The assessment focuses on the human alteration of the Asian S and N cycles, in the context of their global cycles. The role of Asia in contributing to the global emissions of CH_4, CO_2, black carbon, SO_2, NH_3, and NOx will also be included. Case studies on India and China focus on agriculture and the N cycle; see Asia: A Region of Rapid Change.

RESOURCE USE WITH TIME

In 1961, 55% of the world's population lived in Asia. They used far less of the world's fertilizer (22%) and consumed far less of the world's cereal (37%) and meat (13%). In 2004, the Asian population, relative to the global total, had increased slightly to 60%, but their share of fertilizer, cereal, and meat consumption had increased to 55%, 45%, and 42%, respectively, of the global total (**Figure 1*b–d***) (3). Similar increases have been seen in the production of primary commercial energy, i.e., 17% in 1980 and 32% in 2004 (**Figure 1*a***) (4).

The increased use of resources to produce energy and food required by a growing population (which is also increasing its per capita resource use) has resulted in the desired benefits of more food and more energy (which decreased hunger and increased standards of living), but this also increased the loss of chemicals to the environment, causing chemical, physical, and biological changes that negatively impact both people and ecosystems.

THE REACH OF ASIA VIA THE ATMOSPHERE

To examine the reach of Asia via the atmosphere, we explore spatial patterns in emissions of S, N, and C compounds, the extent of their dispersion, and the impacts of changes in emissions in one region of Asia on deposition patterns in other regions of Asia and beyond.

The production and consumption of resources in Asia can result in the transport of commercial products and waste products to regions outside of Asia via international trade, river flow, and atmospheric advection. An analysis of the regional N cycle of Asia for the mid-1990s showed that all three were important (5). Export of N-containing products (e.g., fertilizer, grain, meat) resulted in the loss of ~5 teragrams (Tg) N yr^{-1}. Export of N via rivers and the atmosphere resulted in the loss of ~17 Tg N yr^{-1} and ~10 Tg N yr^{-1}, respectively. An important aspect of this loss is the extent of transport. Transport of N via rivers to inland seas is by definition within a national boundary. This is also probably the case for riverine N that is discharged to the ocean, because a nation's territory can extend out to a maximum of 350 nautical miles (for resource use) and because most riverine N that is discharged to the ocean is denitrified in the coastal and shelf regions (6).

ASIA: A REGION OF RAPID CHANGE

A recently published global assessment, Global Environment Outlook (GEO4), has a regional focus, including a section on Asia and other Pacific nations (2). The assessment highlights both the rapid changes occurring in Asia and the environmental responses to those changes.

According to GEO4, economic growth in Asia and the Pacific has increased by greater than 5% since 2002, fueled in large part by the large increase in energy use, which has increased by 88% in the period from 1987 to 2004 in Asia and the Pacific, compared to the global average of 36%. With the strong drive for food security, agricultural land use has expanded in all regions but Central Asia. As a consequence, land degradation is reported throughout Asia, raising the question of sustainability.

The rapid increase in both energy and food production has resulted in significant impacts on human and ecosystem health.

- More than 1 billion people in Asian countries are exposed to outdoor air pollutant levels exceeding WHO guidelines.
- Asia has the world's highest burden of disease attributable to indoor air pollution.
- Approximately 18% of this population lacks access to safe water.
- Asia and the Pacific nations have ~59% of the world's remaining mangrove forests and 75% of the world's coral reefs. Large fractions of both are at risk due to industrial and infrastructure development.

Transport of N via the atmosphere generally is more extensive. There are two scales—global and regional. Transport occurs on the global scale for N_2O. All emitted N_2O contributes to the global atmospheric burden, given its tropospheric residence time of 114 years. And it is significant—35% of the anthropogenic N_2O emitted to the global atmosphere comes from Asia (7). Transport of NOy and NHx is significant and occurs on the regional scale given the shorter residence times (i.e., days). The ultimate deposition of these N species can be an important source of N to ecosystems outside of Asia. There are certainly consequences once the N is deposited to continental ecosystems (8), and there are likely consequences to marine ecosystems (9).

Transport of N-containing commodities via export is different from riverine and atmospheric transport in two ways. First, it goes further. By definition, the transport is international, and much is intercontinental. Second, the embedded N is not diluted during the transportation process but rather remains in its original concentration in the fertilizer, grain, or meat commodity. It is not until the commodity is consumed in the importing country that dispersion to the environment begins. An interesting aspect of this trade is that the importing countries are getting the benefit of the

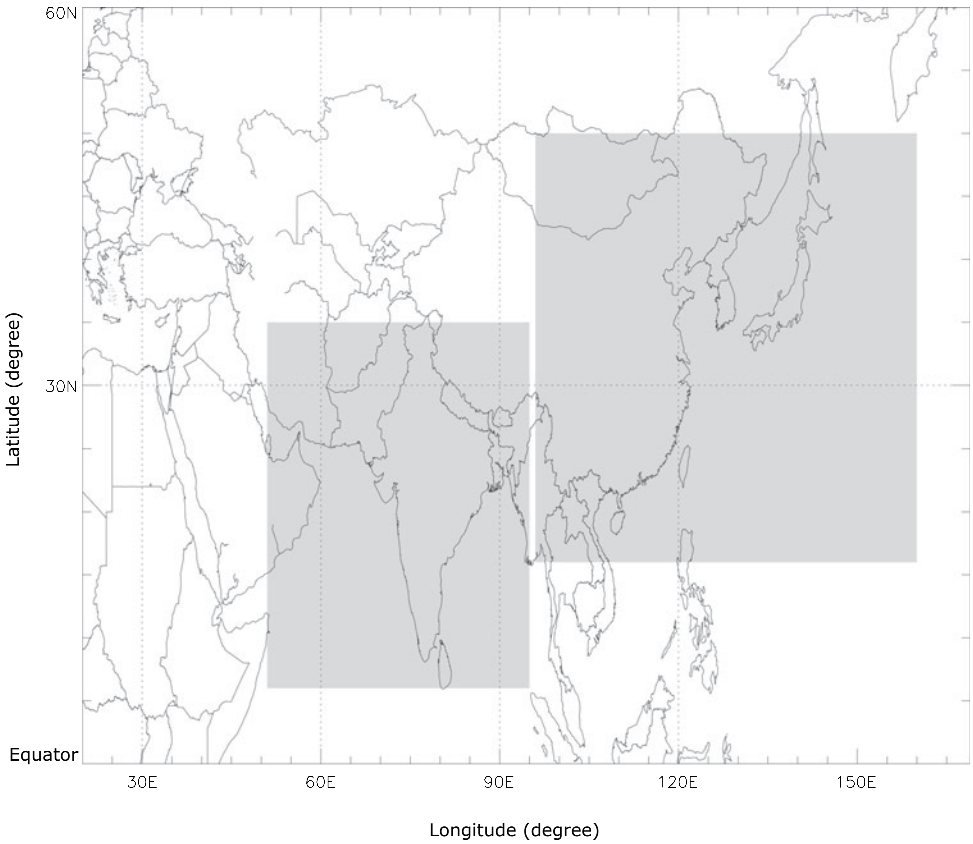

Figure 2

South Asia and East Asia according to the Task Force for Hemispheric Transport of Air Pollution (12). The gray boxes indicate the geographical extent of these regions.

product without having to pay for the environmental and human health costs of making the product—those are borne by the exporting country (10, 11).

The increasing demand for food, transport, and energy in Asia has led to a large growth in emissions, and the effects are felt far away from the source regions. We now look at the degree to which emissions of NOy, NHx, SO_2, and black carbon from one part of Asia contribute to deposition within Asia and outside of Asia. We use the definitions of the Task Force for Hemispheric Transport of Air Pollution (**http://www.htap.org**) to subdivide Asia into two regions—South Asia (India, Pakistan) and East Asia (mainly China) (**Figure 2**).

Emissions and Deposition

Table 1 shows the emissions for East Asia, South Asia, and the world for NOx, SO_2, black carbon, CH_4, NH_3, and CO_2. The emissions are from different literature sources. Black carbon emissions stem from Reference 13. NOx, SO_2, and CH_4 emissions are provided by the International Institute of Applied Systems Applications (14, 15). NH_3 emissions were calculated by the Netherlands Environmental Assessment Agency MNP/IMAGE (formerly RIVM) (16).

The sources contributing to the emissions have varying importance. For example, for NOx emissions, industrial and transport are both important; SO_2 emissions are dominated by industrial and power-generating sectors; and

Table 1 Anthropogenic emissions of NOx (Tg N yr^{-1}), SO_2 (Tg S yr^{-1}), CH_4 (Tg CH_4 yr^{-1}), (14, 15), black carbon (Tg C yr^{-1}) (13), CO_2 (Pg C yr^{-1}) (17, 19), and NH_3 (Tg N yr^{-1}) for East Asia, South Asia, and the world (16)

	East Asia			South Asia			World		
NOx									
	2000	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Industrial/power plant	3.47	—	—	0.97	—	—	13.11	—	—
Domestic	0.41	—	—	0.21	—	—	1.9	—	—
Transport	2.96	—	—	1.49	—	—	20.53	—	—
Total	6.84	8.37	15.51	2.67	5.22	6.96	35.53	41.88	69.74
SO_2									
	East Asia			**South Asia**			**World**		
	2000	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Industrial/power plant	12.29	—	—	3.42	—	—	43.14	—	—
Domestic	2.38	—	—	0.33	—	—	4.7	—	—
Transport	0.49	—	—	0.58	—	—	5.53	—	—
Total	15.16	15.82	28.59	4.33	11.55	16.3	53.37	56.5	98.29
Black carbon									
	East Asia			**South Asia**			**World**		
	2000	**2030 CLE**	**2030 A2**	**2000[ab]**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Fossil fuel	1.21	—	—	0.2	—	—	3.04	—	—
Biofuel	0.44	—	—	0.41	—	—	1.63	—	—
Total	1.65[a]/3.6[b]	3.33[b]	—	0.62[a]/1.52[b]	1.53[b]	—	4.67[a]/ 10.05[b]	8.68[b]	15.1[c]
NH_3									
	East Asia			**South Asia**			**World**		
	2000	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Industrial	0.14	—	—	0.03	—	—	0.4	—	—
Domestic	1.33	—	—	0.72	—	—	4.78	—	—
Agricultural	10.39	—	—	8.39	—	—	43.31	—	—
Total	11.87	11.19	14.95	9.14	15.36	13.76	48.48	58.69	69.38
CH_4									
	East Asia			**South Asia**			**World**		
	2000	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Industrial/fossil fuel	11.38	—	—	6.4	—	—	83.78	—	—
Agricultural	49.66	—	—	52.71	—	—	216.78	—	—
Total	61.04	79.26	85.28	59.11	80.45	85.26	300.56	428.24	456.7
CO_2									
	East Asia			**South Asia**			**World**		
	2000	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**	**2000**	**2030 CLE**	**2030 A2**
Industrial	1.636	—	—	0.426	—	—	7.245	—	—
Biofuel	0.034	—	—	0.042	—	—	0.155	—	—
Deforestation/land use	—	—	—	—	—	—	1.07	—	—
Total	1.672	—	—	0.469	—	—	8.47	9.65	15.92

[a]Bond et al. inventory (13); fossil fuel includes transport.
[b]IIASA inventory (15).
[c]Increase from IPCC Third Assessment Report (17).

Table 2 Percent contribution of East Asia and South Asia to the world's anthropogenic emissions (14, 15)

	NOx	SO_2	Black carbon	NH_3	CH_4
East Asia					
2000	19.3	28.4	35.3	24.5	20.3
2030 CLE	20.0	28.0	38.4	19.1	18.5
2030 A2	22.2	29.1	—	21.5	18.7
South Asia					
2000	7.5	8.1	13.3	18.9	19.7
2030 CLE	12.5	20.4	17.6	26.2	18.8
2030 A2	10.0	16.6	—	19.8	18.7

agricultural emissions are most important for CH_4 and NH_3. Fossil fuel combustion associated with the transportation sector is most important for black carbon. Wood burning for heating and cooking also contributes significant amounts. Different inventories of black carbon emissions vary by as much as a factor of 2–3.

The Current-Legislation (CLE) scenario and the SRES-IPCC-A2 scenarios provide two possible emissions estimates for 2030. The CLE scenario gives the national perspectives on economic growth together with air pollution legislation in place by 2001 (14, 15). The IPCC-A2 scenario is among the more pessimistic emission scenarios used by the Intergovernmental Panel on Climate Change (IPCC) for predicting climate change and assumes a rather large disparity between economic and technological development in the now-industrialized and developing parts of the world (17). By 2030, the CLE scenario still predicts increased levels of almost all emissions, and a large share of these increases results from emissions from East Asia and South Asia. The IPCC-A2 scenario (IPCC 2001) projects even larger increases by 2030 (17).

According to the CLE and IPCC-A2 emission scenarios, absolute emissions from Asia as well as the world's share of environmental and health consequences resulting from Asia's emissions will increase for almost all air pollutants, except for methane (**Table 2**). Although substantial air pollution abatement technology has been implemented in the developed world, there is much room for improvement in developing countries. Strict implementation of air pollution legislation as well as structural changes in energy consumption in Asia can have a positive impact on this development.

The share of East Asian and South Asian anthropogenic emissions relative to the world total in 2000 was 27% for NOx and will grow to 32% in 2030 according to both scenarios. For SO_2, the Asian contribution increases from 37% to 45% to 48%. A large fraction (43%) of the anthropogenic ammonia in 2000 was emitted in East and South Asia, and in the future, this will fluctuate between 41% (IPCC-A2) and 45% (CLE). About 50% of the global anthropogenic black carbon in 2000 was emitted in South and East Asia and will increase to 55% in 2030 (CLE) (**Table 2**). The proportion of CH_4 emitted in Asia at present and in the future is about 40% (15, 17).

The absolute emissions from Asia as well as the world's share of emissions from Asia are in most instances increasing over the next decades, according to the CLE and IPCC-A2 emission scenarios. In other words, the reach of Asia is getting stronger. These increases in air pollutant emissions are driven by economic development and increases in energy use, factors also leading to increases in the world's CO_2 emissions.

There is substantial spatial variability in the emission patterns for NOx, SO_2, NH_3, black carbon, and CH_4 (**Figure 3**) (18, 19). Intensive plumes of NOx, SO_2, and black carbon can be observed over important industrial regions often coexisting with densely populated areas, such as the Ganges River valley in South Asia and in Southeast China (East Asia). Over East China, we find the peak of SO_2 emissions related to the use of coal, which contains high levels of S. Levels of emissions are generally higher over industrial parts of China compared to South Asia and are associated with extremely high concentrations of particulate matter, according to a recent World Bank Assessment (20). Emissions of NH_3 and CH_4, resulting from agricultural activity, are elevated in the extended rural parts of Asia (**Figure 3**). Large ruminant populations emit both NH_3 and CH_4 (21). Emissions of NH_3 and CH_4 from livestock are expected to increase because the number of animals is expected to increase (22). In contrast, CH_4 emissions from rice production decreased–not increased–in recent years.

Model Calculations of Transport and Deposition of Air Pollutants

Once emitted, there is significant dispersal of total S (SO_4 and SO_2), NOx, NH_3, and black carbon (**Figure 4**). We illustrate this dispersal with the global chemistry transport model TM5 (23, 24), which has a resolution of $1^\circ \times 1^\circ$ over Asia.

For total S in 2000, in keeping with the extensive level of fossil fuel combustion in East Asia, S deposition can exceed 5000 mg S m^{-2} yr^{-1}, which is among the highest values in the world. There is a deposition plume that extends to other countries and out to the Pacific Ocean.

The patterns of NOy and NHx deposition are different, reflecting differences in emissions. High NOy deposition is found in eastern China. Even higher levels of NHx deposition are seen in both East and South Asia, reflecting the contribution of agriculture to N emissions to the atmosphere.

Black carbon deposition is a good tracer for primary emissions, resulting from combustion processes (e.g., fossil fuel and wood). Because fossil fuel combustion in East Asia is greater than that in South Asia, the deposition rates in East Asia are an order of magnitude greater than those in most of South Asia. This fact is important because black carbon aerosols play an important role in health and climate issues. Levels of emissions and depositions are generally lower than those of N and S, and to our knowledge, no direct effects on ecosystem health are known.

S and N emissions have impacts on ecosystems. We use a threshold of 1 g N m^{-2} yr^{-1} (critical load) for N deposition to indicate potential risk for ecosystems (25). N depositions above this threshold are found throughout Asia. When the world is considered as a whole, currently 11% of natural vegetation receives N deposition above this threshold (25). The regions of most concern are the United States (20% of vegetation), Western Europe (30%), Eastern Europe (80%), South Asia (60%), East Asia (40%), Southeast Asia (30%), and Japan (50%). These numbers may increase to 80% and 50% by 2030 for South Asia and East Asia, respectively (24). A large contribution of the N deposition to Asia comes from NHx.

The threshold level for damaging acidification by sulfate and nitrate is less clear because it depends on the compensating (buffering) capacity of alkaline mineral dust, the buffering capacity of the receiving soil, and the acidifying (through oxidation) potential of NHx deposition. Rodhe et al. (26) show that large parts of China receive net inputs of acid deposition and that ammonia oxidation in N-saturated ecosystems may further strongly contribute to acidification. This may not be true especially for N-saturated ecosystems (27). Hicks et al. (28) conclude that, at present, except for China, there is little evidence for acidification impacts in Asia. However, sensitive soil types in Southeast Asia, including parts of southern China, Burma, Hainan, Laos, Thailand, Vietnam, and the Western Ghats of India, may acidify on the 50-year timescale.

Contribution of Individual Source Regions

Atmospheric emissions of S and N species (**Figure 3**) in one location are transported and deposited to other locations (**Figure 4**)—the reach of Asia, as it were. The subsequent deposition has negative impacts on both people and ecosystems. This has led to programs of emission control, but it leaves unanswered the question: What is the contribution of individual source regions to these depositions?

In order to evaluate this contribution, we performed two sensitivity studies. In one, the emissions in South Asia have been reduced by 20%, while the emissions in other regions have been kept constant (defined as SR6SA). In the other, the emissions in East Asia have been reduced by 20% (SR6EA). To determine the changes in atmospheric concentrations and depositions of air pollutants caused by this reduction, the results of each study were subtracted from the control run (defined as SR1) (**Figure 5**). Note that the negative perturbation of 20% was chosen to avoid large nonlinear effects. Nonlinear effects are generally considered to be less large for aerosols (29, 30).

The transport patterns for emissions and reaction products in South Asia and East Asia are very different. Transport from East Asia follows a predominantly eastward direction, transporting pollution over Korea and Japan over the Pacific Ocean. The pollution can travel over long distances as can be seen (**Figure 5**) in the perturbation signal declining to 10% of the peak values on distances of 3000–4000 km. It is known from long-range transport studies of other components that episodically desert dust (31) and carbon monoxide (32) can reach the middle of the Northern Pacific Ocean and the West Coast of America. There is little transport from East Asia to South Asia because the Himalayan Mountains block transport.

For South Asia, the monsoon circulation determines transport. In winter, a northeastern circulation prevails, and in general, large atmospheric stability traps pollution in the boundary layer. In summer, hot and humid air from the southwest is pushed toward the Himalayan Mountains, associated with heavy rainfalls. Thus, the distance of influence of South Asia is smaller than for China with 1000–2000 km, illustrating the difference in midlatitude and tropical transport mechanisms. Owing to the predominant wind direction and location of the pollutant sources, there is relatively little transport from China to India.

NOx emissions, together with hydrocarbons, are precursors of tropospheric ozone (O_3), which is an air pollutant as well as a short-lived greenhouse gas. The lifetime of O_3 is about 20 days, which is substantially longer than that of NOx. This means that O_3 can be transported through the atmosphere over long distances. As a result, the Task Force on Hemispheric Transport of Air Pollutants (**http://www.htap.org**) (12) estimates that reducing the emissions by 20% of volatile organic compounds, CO and NOx in North America, Europe, and East Asia combined, will result in surface O_3 reduction in South Asia that is about half of what can be reached by performing the same emission reduction in South Asia itself. In other words, the combined impact of the three foreign regions on surface O_3 in East Asia is about 75% of the domestic signal. As for the impact of emission reductions in South Asia on the surface O_3 in East Asia and vice versa, it was found that emission reductions in East Asia result in surface O_3 reduction in South Asia of 15% compared to the domestic signal, and the impact of South Asia on the surface O_3 in East Asia amounts to 20%.

Extrapolation from the emissions perturbation experiments to the impact of all anthropogenic emissions in a continent indicates that switching off all anthropogenic emissions in South Asia could reduce annual average surface O_3 by about 1 ppb in East Asia. Likewise, the influence of anthropogenic emissions from East Asia on South Asia amounts to about 0.7 ppbv. Although these interregional influences are relatively small compared to the current O_3 concentrations of 40–60 ppbv, the large growth rates in the economy and in emissions seen in South Asia and East Asia over the past decades provide the context for the potential impact (33, 34).

Table 3 Percentage of anthropogenic emissions from East Asia (EA) and South Asia (SA) deposited in receptor regions

	NOy		NHx		S		Black carbon	
Location of deposition	EA	SA	EA	SA	EA	SA	EA	SA
Within the region	81.4	69.6	91.4	80.4	93.5	63.2	85.3	30.9
To the other region	0.9	4.3	1.8	4.2	0.6	4.2	2.9	25.2
To the rest of world	18.6	26.1	6.8	14.9	6.2	31.6	14.7	43.9

Future Deposition

Emissions of NHx, NOx, and SO_2 were estimated for 2030 using the CLE and the IPCC-A2 scenarios (IPCC 2001) (**Table 1**). We use these emission scenarios and the global chemistry transport model TM5 (23, 24) to predict spatial patterns of deposition for 2030. The results are shown as relative increases in reactive N (NOy + NHx) and S deposition over Asia (**Figure 6**).

According to the CLE scenario, N deposition will increase by 50% to 80% over South Asia, mainly because of growing NH_3 emissions. In China, N depositions will grow by 20% as a result of pollution controls. In contrast, in the IPCC-A2 scenario, N deposition increases by 40% to 60% over both China and India.

In the CLE scenario, S emissions are controlled by legislation in China, leading to a stabilization of S deposition by 2030. In India, where less air pollution legislation is in place, larger increases in S deposition—by a factor of two or more—may occur in 2030. In contrast, the IPCC-A2 predicts large increases in emissions and deposition everywhere throughout the region.

The long-range transport of pollution from South Asia and East Asia is expressed as a source-receptor matrix in **Table 3**. Between 6.2% and 18.6% of NOy, NHx, S, and black carbon is exported from East Asia to the rest of the world, and relatively little to South Asia. Between 4% and 25% of the anthropogenic emissions is transported from South Asia to East Asia, and between 15% and 44% to the rest of the world.

AGRICULTURE AS A DRIVER OF ENVIRONMENTAL CHANGES IN CHINA AND INDIA

The world's two largest countries are China and India, with 2004 populations of 1.3 and 1.1 billion people, respectively. Over the past several decades, the growing populations and increased standard of living have resulted in large increases in consumption of energy, cereal, and meat (**Figure 7**). These increases have resulted in substantial creation of reactive N by accident (energy production) and on purpose (N fertilizer for food production). We now look at the impact of agriculture on the N cycle of China and India and the associated impacts on human and environmental health.

Impact of Agriculture on the N Cycle of China

The consumption of N fertilizers has increased continuously in China since 1961 and can be divided into three stages (**Figure 8**) (35, 36). From 1961 until the end of the Cultural Revolution in 1976, N consumption increased at a relatively low rate. In the first several years after the Cultural Revolution, consumption increased at a very high rate and reached a peak of 25.3 Tg in 1996. After that, it dropped slightly. In recent years, consumption of N fertilizers increased again to match the demand for food production (**Figure 8**). Calculated by total crop harvested area and total consumption of N fertilizers, the average N application rate per crop harvested area reached 171 kg N hectare^{-1} (ha^{-1}) in 2005 and ranged from 71 kg N ha^{-1} to ~300 kg N ha^{-1}. The N application rate in coastal areas

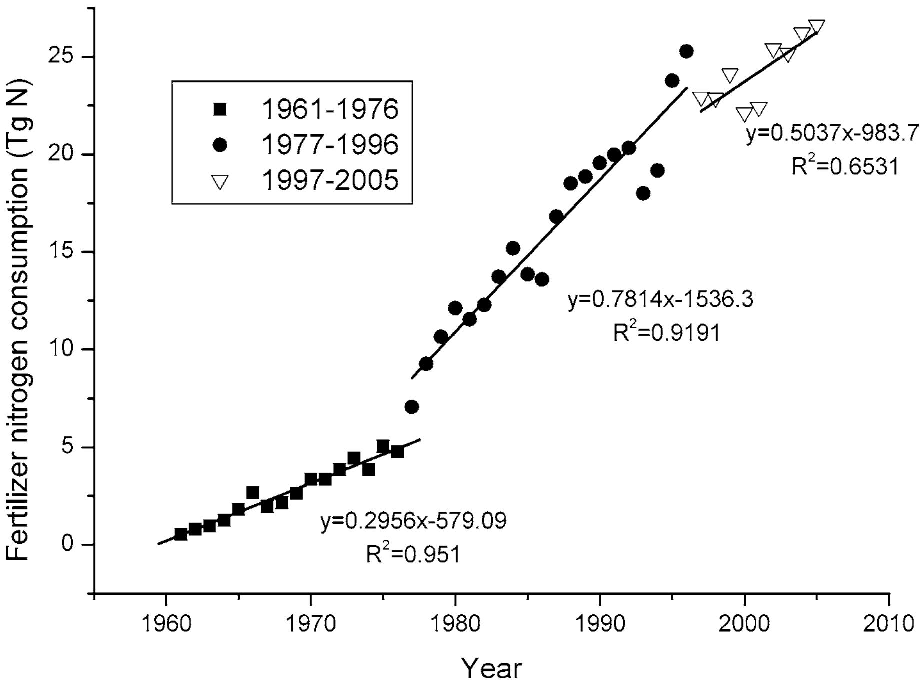

Figure 8

Temporal variation of total consumption of N fertilizers in China from 1961 to 2006 (35, 36).

was much higher than that in western China. Heilongjiang province had the lowest rate of N application, and Beijing the highest.

Although food security is always a critical issue in China, cereal production did not increase substantially over the past two decades and in the last decade has actually diminished somewhat as a result of the competing pressures of development and conversion to other crops, such as vegetables, production of which is increasing because it is preferred for economic reasons (**Figure 9**). This type of agriculture is usually very intensive. With a very large multicropping index, the annual N application rate could reach more than 1000 kg N ha^{-1} in many vegetable fields (37). Intensive vegetable production has led to serious problems, such as soil acidification and nitrate leaching (37, 38).

Meat production, a driver of growing importance. Meat consumption is increasing in China as its economy develops. The demand for meat stimulates the growth of farms for raising livestock, e.g., cattle, chickens, and pigs (**Figure 10**). It is projected that the number of animals in 2020 will be 1.67 times that of 2001 (39). Assuming that animal wastes increase in proportion to the increase in the number of animals, the total of animal wastes is projected to be about 3200 megatonnes (Mt) in 2020.

Most of the large livestock farms are located in eastern China. Total animal wastes were estimated to be 1900 Mt in 1999, larger than the sum of waste materials produced from industry and humans (39). Freshwater fisheries are also increasing at a high rate. From 1985 to 2005, the total area for freshwater fish aquaculture increased by ~59%, and of this, the area made up of fish ponds increased by ~100% (36). Because fish feeds enriched with N are directly put into the water and N-use efficiency is low, freshwater fisheries have become an important source of N pollution in water.

Environmental problems. Chemical N fertilizer input plays a critical role in supplying

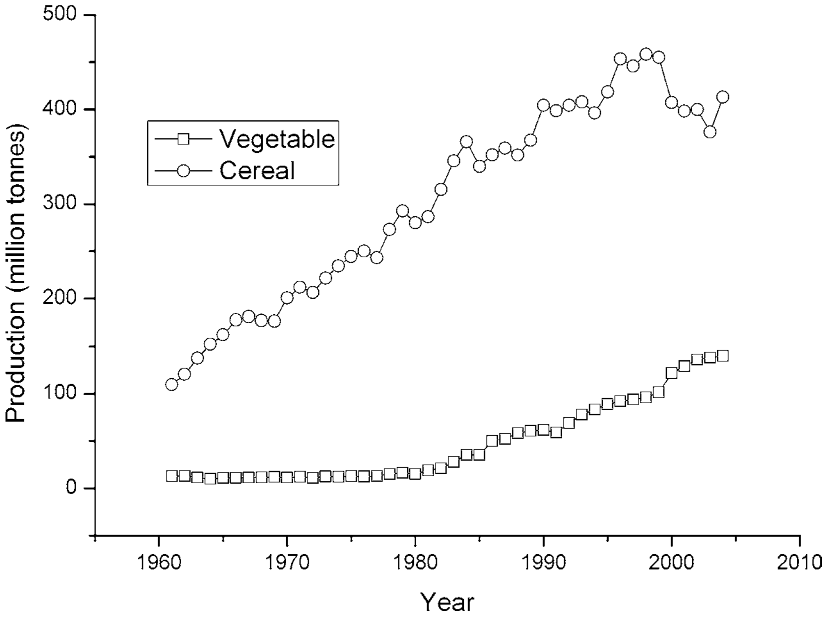

Figure 9

Cereal (*circles*) and vegetable (*squares*) production in China from 1961 to 2004 (3).

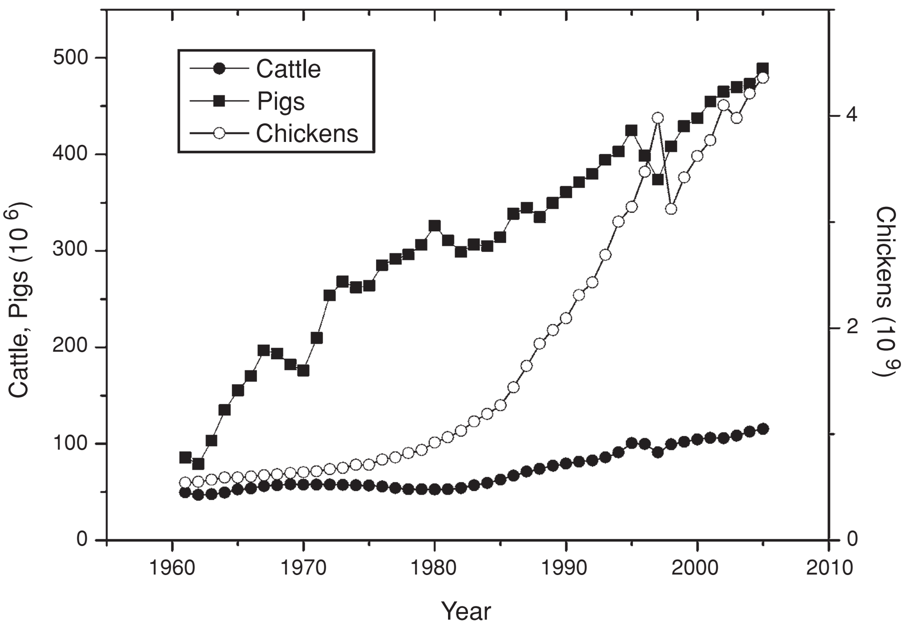

Figure 10

Number of cattle, pigs, and chickens in China from 1961 to 2005 (35).

China's population with cereals, vegetables, meat, and fiber. Yet the increase in chemical N fertilizer consumption has resulted in serious environmental problems. Other contributors to environmental problems are the quick and intensive growth of livestock development, vegetable production, and freshwater fisheries with very large annual N inputs, as well as the uneven spatial distribution of these activities, which are much more intensive in the eastern coastal regions than in the western regions of China.

One of the problems, surface water eutrophication, directly influences local citizens' quality of life. For example, Dianchi Lake (300 km^2) used to be the main tap water resource for Kunming City, capital of Yunnan province. It is now supereutrophied and cannot be used as a tap water source (40). Likewise, Taihu Lake has suffered from algal blooms, a direct consequence of eutrophication. With an area of 2250 km^2 and a location at the delta of the Yangtze River, traversing Shanghai, Jiangsu, and Zhejiang provinces, the impact of pollution to Taihu Lake is felt widely. In fact, almost all the lakes distributed along the middle and lower reaches of the Yangtze River have been eutrophied to some degree (41).

In northern China, NO_3^- is accumulating in groundwater associated with soils that have strong nitrification activity owing to excessive or unbalanced N fertilization. Long-term experiments showed that, when N chemical fertilizer or large amounts of organic manure were applied, huge amounts of NO_3^- (up to 600 kg ha^{-1} in soil profile to 4 m) accumulated in the soil profile and in the groundwater (42, 43). A survey conducted in the mid-1990s showed that NO_3^- concentration in more than 50% of the surveyed well water in northern China was above the human health limit for drinking water (44).

China is one of the regions of the world with the highest NH_3 (**Figure 3**) and N_2O emissions (45, 46), although there are uncertainties in the inventories of nitrogenous gases emitted to the atmosphere. Streets et al. (47) estimated that in 2000 NH_3 emissions from China reached 13.6 Tg NH_3. The total N_2O emissions from croplands of China, estimated by the Denitrification-Decomposition model, were 0.31 Tg N in 1990 (46). By using an empirical model, Lu et al. (48) estimated that in 1997 the total N_2O emission from China's croplands was 0.29 Tg N yr^{-1}, of which 0.09 Tg N came from background emissions and 0.20 Tg N came from N fertilizers applied. The estimated smaller N_2O emissions in 1997 than in 1990 do not mean a decreasing trend of N_2O emissions from croplands in China but rather reflect uncertainties in the estimate.

The large emissions of NH_3 (and NOx) result in substantial rates of N deposition in China (**Figure 4**). Fan et al. (49) estimated that the annual N deposition on forestland in subtropical China was up to 82.8 kg N ha^{-1}. Based on N balance in a long-term experiment without N application, average annual N deposition in northern China from 1990 to 2003 was calculated to be more than 50 kg N ha^{-1} (50). The wet deposition alone in China was much larger than the world average (5). Through atmospheric transport and deposition, the ecosystems without direct N application receive a substantial amount of N. This level of deposition is similar to levels of N application used for some agricultural crops and not only represents a large input of N to unmanaged ecosystems, but is also larger than the critical loads for unmanaged terrestrial and aquatic ecosystems (8).

With the rapid increase in N input, N transport through rivers into seas is increasing as well. On the basis of measurements conducted at the Datong station at the lower reach of the Yangtze River, the concentration of dissolved N increased abruptly after the 1980s (51), responding to the steep increase in the consumption of N fertilizers (**Figure 8**). Shen (52) estimated that the total flux of N from the Yangtze River to the sea was 2.85 Tg N, of which 1.75 Tg N was dissolved inorganic N in 1998, double the amount, 0.89 Tg N, in 1985. According to Chai et al. (53), nitrate concentration in the Yangtze River estuary and the adjacent East China Sea increased from 11 to 97 μmol L^{-1} from 1963 to 2004 and N:P ratios increased from 30–40 up to 150. In parallel with the N and P enrichment, a significant increase in Chl-a—to a maximum of 20 mg/m^3—was detected, nearly four times higher than in the 1980s.

Although there is growing knowledge concerning human alteration of the N cycle and its consequences on the local scale, such understanding is very limited on the national scale. There are large uncertainties in the estimates of N_2O, NOx, and NH_3 emissions from agricultural sectors. Except for data on theYangtze River, the literature has few references to data on N fluxes to seas from other rivers. Research on this front must be strengthened.

Looking ahead. China's rapid economic development over the past two decades has been accompanied by natural resource shortages and environmental pollution, which have limited further economic development. This has resulted in a shift in China from a sole focus on economic prosperity to a balanced approach considering both economic and ecological concerns. The well-publicized algal bloom caused by excess N and P in May 2007 compromised water quality for the city of Wuxi (3 million people) to such a degree that the drinking water supply was turned off. The direct impact of this event on central and local policy makers was to alter the process for evaluating governmental officers; no longer will they be evaluated only on the increase in GDP they garner; rather an index of local environmental quality will also be used. Although it will take some time to reverse the environmental degradation in China, this effort and others are steps in the right direction.

Impact of Agriculture on the N Cycle of India

Wide variations in the natural environment of India are profoundly manifested in Indian agriculture. Accordingly, the country is divided into arid, rain-fed, coastal, hill and mountain, and irrigated agroecosystems (54). A large percentage of cultivated area (61%) is rain-fed extending to over 87 Mha. Rice-wheat is the major cropping system practiced in India (10 Mha), and it accounts for about one-third of the food grain production (55). In addition, India has one of the highest concentrations of livestock in the world, but livestock are usually raised as part of mixed farming, and animals mainly depend on crop residues and crop by-products.

In the past four decades, India has greatly improved its agricultural practices. There has been a corresponding increase in N fertilizer use from 0.065 Mt in the early 1950s to 11.3 Mt in 2001 and 2002. Food grain projections for 2020 indicated that per capita production is expected to decline from 171 to 162 kg yr^{-1}, and demand will rise from 157 to 180 kg yr^{-1} from 2005 to 2020 (56). As a result of these pressures and the projected future demands for grain, there has been and will continue to be a marked change in the supply and use of land, water, fertilizer, seeds, and livestock. These changes are linked to the N cycle and significantly alter the N pools and fluxes in the various agroecosystems of India. Hence, assessing the N cycle at the regional level is valuable for addressing region-specific environmental policy questions.

Land use. In the past century, India has experienced a conversion of its natural landscapes to a highly managed ecosystem. Urban growth and land degradation of different types and intensity have been coupled with higher population growth. Net sown area increased by 23 Mha from 1950–1951 to 2000–2001 (119 to 141 Mha). Also during this period, cropping intensity increased by 18%, resulting in an increased gross cropped area of 55.6 Mha (from 132 Mha to 188 Mha) (**Figure 11**) (57). The loss of forest owing to the expansion of cropland area has resulted in a decrease in the vegetation N pool (58). In addition, nonforested wetland area decreased by 11% from 1950–1951 to 1992–1993 (59). The loss of wetlands has resulted in N mobilization by accelerating the mineralization process, which leads to loss of organic matter. Long-term experiments by Nambiar (60) and Sinha et al. (61) have shown a decrease in soil organic matter throughout the rice-wheat system of India and the loss of soil carbon (from 0.5% in the 1960s to 0.2%

Table 4 Production and yield of important crops in India (62)

Crops and years	Area (Mha)	Production (Mt)	Irrigated (%)	Yield (kg/ha)
Food grains				
1950–1951	97.3	50.8	18.1	522
2000–2001	121	197	43.4	1626
Total pulses				
1950–1951	19.1	8.4	9.4	441
2000–2001	20.4	11.1	12.5	544
Oil seeds				
1950–1951	10.7	5.2	NA	481
2000–2001	22.8	18.4	23	810
Fruits 2000–2001	4.0	43.1	—	—
Vegetables 2000–2001	6.2	88.6	—	—

in the 1990s) from Indian soils. Land conversion denotes bringing more area under agricultural land use, whereas land modification describes the input-intensive agriculture that also includes more N fertilizer use.

Trends in crop production and impact on crop N pool. The adoption of modern green revolution technologies through crop rotation, among other inputs, has increased the production of food grains, pulses, oil seeds, fruits, and vegetables many fold (**Table 4**) (62). As a result, the crop N pool increased from 2.94 Tg N (1950–1951) to 12.47 Tg N (1995–1996), and more N entered into the human and animal food chain. Furthermore, the application of more N fertilizer to meet the demand of N-responsive crop varieties enhanced the recycling of N among soil, plant, and atmosphere. Approximately 30% of N from the chemical fertilizers used is removed annually by crop residues. These residues have the potential to be recycled, decreasing the need for new N creation as well as decreasing the cost of N fertilizer.

Rice-wheat is the major crop rotation practiced in India (9.8 Mha) followed by rice-rice (5.9 Mha) and rice-fallow (4.4 Mha). However, the rice-wheat system has started showing signs of production fatigue, and the rice-rice system is suffering from soil fertility problems (63). Moreover, rice has low N fertilizer-use efficiency. Under such situations, crop diversification and N-use efficiency have assumed paramount importance to stabilize production and reduce N lost to the environment.

Human activity through deforestation and other land-use changes is also speeding up the release of N from long-term storage in soils and organic matter (64). These anthropogenic changes to the global N cycle, in turn, could significantly change the composition, productivity, and other properties of many natural ecosystems (65).

Use of quality seeds of high-yielding varieties has increased production and contributed to the increasing storage of seeds for consumption as well as for agricultural purposes. This means a substantial portion of N (~0.5 to 0.7 Tg N) is stored in organic form away from the current production system. But increased use of seeds of high-yielding varieties without proper N management strategies not only exhausts the soil N pool but also affects the soil N flux.

Fertilizer use. The possibility for increases in crop productivity without inorganic nutrient use is limited because Indian soils are reported to have low total N and organic matter content owing to the tropical and subtropical climate prevailing in the country (66). Annual N fertilizer use in Indian agriculture has increased to 10.9 Mt in 2000–2001 from 0.065 Mt in the early 1950s apart from organic sources. In 1995–1996, nearly 10.8, 0.17, and 15.6 Tg N (1995–1996) was added into the agroecosystem through inorganic N fertilizers, compost (67), and livestock manures (68), respectively.

There are large state-level variations in total N fertilizer consumption as well as intensity of N use. The intensity of N fertilizer use increased by 138% (0.44 to 61.3 kg ha^{-1}) from 1950–1951 to 1999–2000, especially because of the green revolution (69). The intensity of N use is more in the Indo-Gangetic plains and peninsular coastal areas (70). However, N recovery efficiency for fields managed by farmers ranges from 20% to 30% under rain-fed conditions and 30% to 40% under irrigated conditions, leading to a loss of N into the environment (71). In addition, organic sources of N, such as manures and/or biological N fixation (BNF), are also used across different cropping systems. BNF through biofertilizer addition has increased from 0.55 Tg N to 1.14–1.18 Tg N from 1950–1951 to 1995–1996. Furthermore, the biofertilizer demand for 2011 has been estimated at 30,000 t, indicating the possibility of more N addition through BNF in the future (67, 68). Finally, substantial amounts of organic manures from forest ecosystems are used in agriculture when the source is nearby, adding to the N load.

Livestock. From 1951 to 1992, the bovine population increased from 199 million to 283 million. Likewise, numbers of sheep increased from 39 million to 61 million and goats from 47 million to 124 million. These represent increases of 42%, 56%, and 64%, respectively. Beginning with "Operation White Flood" (1969–1970), which aimed to increase the production of milk and milk products, significant changes occurred in the breeds of animals and in animal production technology. These changes contributed to the increase in the livestock N pool from 0.97 to 1.62 Tg N.

The seventeenth livestock census of India found that, although there was no significant change in the total livestock population (−0.08%) over 1997 (485 million), the number of crossbred cattle has increased by 23%, and the number of indigenous cattle decreased by 10% (72). This has resulted in a larger amount of N entering the livestock N pool because crossbred populations are fed more concentrated feeds. Note that the amount of feed and fodder used for livestock is largely unquantified, implying an uncertainty in the livestock input N fluxes estimation. N flux through livestock waste production in India increased from 1.04 Tg N in 1951 to 1.53 Tg N in 1992 (68). Because animal manure nutrient-use efficiencies are often low, this results in significant N losses to water and/or the atmosphere.

Impact of irrigation. The net irrigated area in India increased from 20.8 Mha in 1950–1951 to 56.8 Mha in 2000–2001. Such an increase has had profound effects in modifying N pools and fluxes. Excessive irrigation and the increased intensity of N fertilizer use have resulted in secondary salinization and NO_3^- pollution of groundwater. Results of surveys conducted to assess the nitrate content of groundwater showed very high nitrate concentrations (Uttar Pradesh, 300–694 ppm; Punjab, 362–567 ppm; Haryana, 300–1310 ppm) (73). In Karnataka, a large number of districts have been affected by NO_3^- pollution; the worst affected were Tumkur (35%), Mysore (20%), and Kolar (21%) (the figures in parentheses indicate percentage of villages affected by nitrate pollution out of total villages in a district) (74). High nitrate levels in groundwater pose serious health hazards, yet some of the N in groundwater is brought back into the new crop production cycle by irrigation.

Environmental problems. Excessive N losses in the form of N_2O, NOx, and NH_3 from agricultural activity will have harmful environmental impacts. Estimates for N_2O emission from all agricultural activity were 0.24 Tg (75); fertilizer use, 0.016 Tg (76); burning of biomass, 0.011 Tg (75); biological N fixation, 0.01 Tg; and livestock, 0.01 Tg (76). The reported NOx emission from biomass burning was 0.4 Tg (75) and 0.66 Tg (77). Streets et al. (47) have estimated that in 2000 NH_3 emissions from India reached 7.4 Tg NH_3. These values may change across various agroecosystems as the amount of ammonia lost to the atmosphere from soil through volatilization is affected by the rate of N application, modified forms of urea, the source of N, and the moisture content of soil (78). Considering the rate of change in N addition through inorganic fertilizers, BNF, and biomass burning from 1950 to 1995, a nearly 10% to 15% increase in N flux (as N_2O) from soil to atmosphere might have occurred in each decade to reach the current level of 0.24–0.26 Tg N yr^{-1}.

As both agricultural and industrial activities intensify, N released into the environment will have both direct (water and air pollution) and indirect (ecological feedbacks to disease) health consequences. Rao & Puttanna (79) reported that, in the agriculturally intensive areas in Punjab, Delhi, Maharashtra, and Andhra Pradesh, groundwater had more than the WHO permissible potable water limit of 10 ppm NO_3^-. Among the health effects of nitrates and nitrites in food is methemoglobinemia in babies, wherein the oxygen carrying capacity of red blood cells is reduced or lost (80). Usha et al. (81) studied the dietary intake of nitrates in Andhra Pradesh and reported that NO_3^- contents of cereal ranged from 20 to 76 mg kg^{-1}; pulses, 39 to 114 mg kg^{-1}; and leafy vegetables, 30 to 270 mg kg^{-1}. The maximum admissible level of nitrite is 1 mg kg^{-1}. An increase in N radicals in the air caused decreased rainfall pH (rain acidification) in 10 of India's background air pollution monitoring stations (82). Furthermore, N-fueled eutrophication of marine coastal waters contributes to harmful algal blooms and fish kills, as roughly 25% of the fertilizers used are expected to end up in the sea every year (83).

Looking ahead. In the postgreen revolution period, India has been experiencing changes in N pools and fluxes indicating the potential loss of N into the environment with increased health concerns. Land-use patterns and agricultural management practices change year by year, and climatic fluctuations result in annual variations that are reflected in biological activity and thus in N fluxes in various agroecosystems of India. Too few studies have been done in which N losses have been measured in on-farm settings across a reasonable range of representative environments and spatial scales. Even at high production levels, N utilization efficiency can be increased by adoption of improved management practices provided that substantial investments are made in research and extension.

Restoration of degraded soils in India is expected to reduce N use and lock up or increase the residential time of some of this N in organic form. With increased understanding of N cycling in agroecosystems, all efforts should be made to maintain the soil surface N balance, resulting in crop yields with minimal fertilizer wastage, financial benefits, and a reduction in environmental losses of N.

SUMMARY POINTS

1. A grand experiment in human alteration of the natural environment began in Asia thousands of years ago.
2. This alteration has resulted in a food and energy supply system that now supports ~4 billion people.
3. The same supply system causes losses of S, C, and N compounds to the environment that contribute to significant negative impacts to both ecosystems and human health.
4. Much of the S, C, and N that is lost to the environment is emitted to the atmosphere. Transport from East Asia follows a predominantly eastward direction, transporting pollution over Korea and Japan over the Pacific Ocean.

5. There is little transport from East to South Asia. For South Asia, the monsoon circulation determines transport. In winter, a northeastern circulation prevails, and in general, large atmospheric stability traps pollution in the boundary layer. In summer, hot and humid air, associated with heavy rainfalls, from the southwest is pushed toward the Himalayan Mountains. Thus, the distance of influence of South Asia is smaller than for East Asia.

FUTURE ISSUES

1. The Asian population is projected to stabilize by the end of the twenty-first century. It is likely, however, that the impact of the population on the N, S, and C cycles will continue to grow owing to economic growth, which will be manifested in an increased per capita use of resources.
2. The absolute emissions from Asia as well as the world's share of emissions from Asia are in most instances increasing over the next decades, according to the CLE and IPCC-A2 emission scenarios. In other words, the reach of Asia is getting stronger.
3. The current and future global challenge is to implement economic growth scenarios that, on the one hand, will not limit the ability of the Asian population to attain a higher standard of living but, on the other hand, will not result in a continued degradation of the environments within, downwind and downstream of, Asia.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

1. Ruddiman WF. 2007. The early anthropogenic hypothesis: challenges and responses. *Rev. Geophys.* 45:RG4001, doi: 10.1029/2006RG000207
2. UN Environ. Program. (content partn.)/Cleveland CJ. 2007. *Global environment outlook (GEO-4): preface*. In *Encyclopedia of Earth*, ed. CJ Cleveland, Washington, DC: Environ. Inf. Coalit./Natl. Counc. Sci. Environ. **http://www.eoearth.org/article/Global_Environment_Outlook_(GEO-4):_Preface**
3. Food Agric. Organ. UN. 2008. *FAO statistical databases*. **http://faostat.fao.org/default.aspx**
4. Energy Inf. Adm., Dep. Energy. 2007. *International and United States total primary energy consumption*. **http://www.eia.doe.gov/emeu/international/energyconsumption.html**
5. Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, et al. 2004. Nitrogen cycles: past, present and future. *Biogeochemistry* 70:153–226
6. Seitzinger SP, Harrison J, Bohlke J, Bouwman A, Lowrance R, et al. 2006. Denitrification across landscapes and waterscapes: a synthesis. *Ecol. Appl.* 16(6):2064–90

7. Mosier AR, Zhu Z. 2000. Changes in patterns of fertilizer nitrogen use in Asia and its consequences for N_2O emissions from agricultural systems. *Nutr. Cycl. Agroecosyst.* 57:107–17
8. Bobbink R, Hornung M, Roelofs JGM. 1998. The effects of air-borne nitrogen pollutants on species diversity in natural and seminatural European vegetation. *J. Ecol.* 86(5):717–38
9. Duce RA, LaRoche J, Altieri K, Arrigo K, Baker A, et al. 2008. Impacts of atmospheric anthropogenic nitrogen on the open ocean. *Science* 320:893–97
10. Naylor R, Steinfeld H, Falcon W, Galloway J, Smil V, et al. 2005. Losing the links between livestock and land. *Science* 310:1621–22
11. Galloway JN, Burke M, Bradford GE, Naylor R, Falcon W, et al. 2007. International trade in meat: the tip of the pork chop. *Ambio* 36:622–29
12. Task Force Hemisph. Transp. Air Pollut. 2007. Interim report: hemispheric transport of air pollution 2007. *Air pollution stud. 16*. UN, New York/Geneva. ISBN 978092-1-116984-3
13. Bond TC, Streets DG, Yarber KF, Nelson SM, Woo JH, Klimont Z. 2004. A technology based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* 109:D14203, doi:10.1029/2003JD003697
14. Dentener F, Stevenson D, Cofala J, Mechler R, Amann M, et al. 2005. The impact of air pollutant and methane emission controls on tropospheric ozone and radiative forcing: CTM calculations for the period 1990–2030. *Atmos. Chem. Phys.* 5:1731–55
15. Cofala J, Amann M, Klimont Z, Kupiainen K, Hoglund-Isaksson L. 2007. Scenarios of global anthropogenic emissions of air pollutants and methane until 2030. *Atmos. Environ.* 41:8486–99
16. Eickhout B, Den Elzen MGJ, Kreileman GJJ. 2004. The atmosphere-ocean system of IMAGE 2.2. A global model approach for atmospheric concentrations, and climate and sea level projections. *Rep. 481508017*, Natl. Inst. Public Health Environ. (RIVM), Bilthoven, Neth.
17. Intergov. Panel Clim. Change. 2001. Climate change 2001: the scientific basis. In *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate*, ed. JT Houghton, Y Ding, DJ Griggs, M Noguer, PJVD Linden, et al, pp. 1–881. Cambridge/New York: Cambridge Univ. Press.
18. Dentener F, Drevet J, Lamarque JF, Bey I, Eickhout B, et al. 2006. Wild, nitrogen and sulphur deposition on regional and global scales: a multi-model evaluation, *Glob. Biogeochem. Cycles* 20:GB4003, doi:10.1029/2005GB002672
19. Olivier JGJ, Van Aardenne JA, Dentener F, Pagliari V, Ganzeveld LN, Peters JAHW. 2005. Recent trends in global greenhouse gas emissions: regional trends 1970–2000 and spatial distribution of key sources in 2000. *Environ. Sci.* 2(2–3):81–99
20. Pandey KD, Wheeler D, Ostro O, Deichmann U, Hamilton K, Bolt K. 2006. *Ambient Particulate Matter Concentrations in Residential and Pollution Hotspot areas of World Cities: New Estimates based on the Global Model of Ambient Particulates (GMAPS)*. World Bank Dev. Econ. Res. Group/Environ. Dep. Work. Pap. Washington, DC. **http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/O,contentMDK:20785646∼pagePK:642414825∼piPK:64214943∼thesitePK:469382,00.htm**
21. Khalil MAK, Shearer MJ. 2006. Decreasing emissions of methane from rice agriculture. In *Greenhouse Gases and Animal Agriculture: An Update*, Int. Congr. Ser. 1293, ed. CR Soliva, J Takahashi, M Kreuzer, pp. 33–41. Amsterdam: Elsevier
22. Li CS, Frolking S, Xiao XM, Moore III B, Boles S, et al. 2005. Modeling impacts of farming management alternatives on CO_2, CH_4, and N_2O emissions: a case study for water management of rice agriculture of China. *Glob. Biogeochem. Cycles* 19(3):GB3010
23. Krol MC, Houweling S, Bregman B, Van Den Broek M, Segers A, et al. 2005. The two-way nested global chemistry-transport zoom model TM5: algorithm and applications. *Atmos. Chem. Phys.* 5:417–32
24. Dentener F, Drevet J, Lamarque JF, Bey I, Eickhout B, et al. 2006. Nitrogen and sulphur deposition on regional and global scales: a multi-model evaluation. *Glob. Biogeochem. Cycles* 20:GB4003, doi:4010.1029/2005GB002672
25. Phoenix GK, Hicks WK, Cinderby S, Kuylenstierna JCI, Stock WD, et al. 2006. Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts. *Glob. Change Biol.* 12:470–76

26. Rodhe H, Dentener F, Schulz M. 2002. The global distribution of acidifying wet deposition. *Environ. Sci. Technol.* 36:4382–88
27. Zhao W, Cai ZC, Xu ZH. 2007. Does ammonium-based N addition influence nitrification and acidification in humid subtropical soils of China? *Plant Soil* 297(1–2):213–21
28. Hicks WK, Kuylenstierna JCI, Owen A, Seip HM, Dentener F, Rodhe H, 2008. Soil sensitivity to acidification in Asia: status and prospects. *Ambio* 37:295–303
29. Kloster S, Dentener F, Feichter J, Raes F, Aardenne JA, et al. 2008. Influence of future air pollution mitigation strategies on total aerosol radiative forcing. *Atmos. Chem. Phys. Discuss.* 8:5563–627
30. Unger N, Shindell DT, Koch DM, Streets DG. 2008. Air pollution radiative forcing from specific emissions sectors at 2030. *J. Geophys. Res.* 113:doi:10.1029/2007JD008683
31. Prospero JM, Uematsu M, Savoie DL. 1989. Mineral aerosol transport to the Pacific Ocean. Vol. 10: *Chemical Oceanography*, pp. 187–218. New York: Academic
32. Jaffe D, Yurganov L, Pullman E, Reuter J, Mahura A, Novelli P. 1998. Measurements of CO and O_3 at Shemya, Alaska. *J. Geophys. Res.* 103(D1):1493–1502
33. Stevenson DS, Dentener FJ, Schultz MG, Ellingsen K, Van Noije TPC, et al. 2006. Multi-model ensemble simulations of present-day and near-future tropospheric ozone. *J. Geophys. Res.* 111:D8, D0830110.1029/2005JD006338
34. Dentener FD, Stevenson D, Ellingsen K, Van Noije TPC, Schultz MG, et al. 2006. Global atmospheric environment for the next generation. *Environ. Sci. Technol.* 40:3586–594
35. Editor. Board China. 2006. *China Agricultural Yearbook*, pp. 159–374. Beijing: Agric. Press
36. Editor. Board China. 2007. *China Agricultural Yearbook*, pp. 160–375. Beijing: Agric. Press
37. Li JL, Cui DJ, Meng XX, Li XL, Zhang FS. 2002. The study of fertilization condition and question in protectorate vegetable in Shouguang, Shandong. *Chin. J. Soil Sci.* 33(2):126–28 (In Chinese)
38. Yang ZP, Zhang JJ, Zhang Q, Chen MC. 2007. Soil environmental quality with long-term fertilization in Shanxi greenhouse. *J. Agro-Environ. Sci.* 26(2):667–71 (In Chinese)
39. Minist. Environ. Prot. Peoples Repub. China. 2002. *Report of the national livestock pollution survey in 2000.* **http://www.sepa.gov.cn/natu/lchj/sjyzy/200201/t20020111_60394.htm**
40. Fang T, Ao HY, Liu JT, Cai QH, Liu YD. 2004. The spatio-temporal variations of water environmental status in Dianchi Lake. *Acta Hydrobiol. Sin.* 28(2):124–30 (In Chinese)
41. Qin B. 2002. Approaches to mechanisms and control of eutrophication of shallow lakes in the middle and lower reaches of the Yangtze River. *J. Lake Sci.* 14(3):193–202 (In Chinese)
42. Fan J, Hao MD, Shao MA. 2003. Nitrate accumulation in soil profile of dry land farming in northwest China. *Pedosphere.* 13(4):367–74
43. Yang SM, Malhi SS, Song JR, Xiong YC, Yue WY, et al. 2006. Crop yield, nitrogen uptake and nitrate-nitrogen accumulation in soil as affected by 23 annual applications of fertilizer and manure in the rainfed region of northwestern China. *Nutr. Cycl. Agroecosyst.* 76(1):81–94
44. Zhang WL, Tian ZX, Zhang N, Li XQ. 1996. Nitrate pollution of groundwater in northern China. *Agric. Ecosyst. Environ.* 59(3):223–31
45. Bouwman AF, Lee DS, Asman WAH, Dentener FJ, VanderHoek KW, Olivier JGJ. 1997. A global high-resolution emission inventory for ammonia. *Glob. Biogeochem. Cycles* 11(4):561–87
46. Li CS, Zhuang YH, Cao MQ, Crill P, Dai ZH, et al. 2001. Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N_2O emissions from arable lands in China. *Nutr. Cycl. Agroecosyst.* 60(1–3):159–75
47. Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, et al. 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res.* 108(D21):8809. doi:10.1029/2002JD003093
48. Lu YY, Huang Y, Zou JW, Zheng XH. 2006. An inventory of N_2O emissions from agriculture in China using precipitation-rectified emission factor and background emission. *Chemosphere* 65(11):1915–24
49. Fan JL, Hu ZY, Zhuang SY, Zhou J, Wang TJ, Liu CY. 2007. Observation of atmospheric nitrogen deposition into forestland. *China Environ. Sci.* 27(1):7–9 (In Chinese)
50. Cai ZC, Qin SW. 2006. Crop yield, N use efficiency and environmental impact of a long-term fertilization experiment in Fluvo-Aquic soil in North China. *Acta Peodologica Sin.* 43(6):885–91 (In Chinese)

51. Li MT, Xu KQ, Watanabe M, Chen ZY. 2007. Long-term variations in dissolved silicate, nitrogen, and phosphorus flux from the Yangtze River into the East China Sea and impacts on estuarine ecosystem. *Estuar. Coast. Shelf Sci.* 71(1–2):3–12
52. Shen Z. 2004. Nitrogen transport fluxes in the Yangtze River. *Adv. Water Sci.* 15(6):752–59 (In Chinese)
53. Chai C, Yu ZM, Song XX, Cao XH. 2006. The status and characteristics of eutrophication in the Yangtze River (Changjiang) estuary and the adjacent East China Sea, China. *Hydrobiologia* 563:313–28
54. Ramakrishna VS, Rao GGSN, Desava-Rao AVR, Vijaya-Kumar P. 2000. Weather resource management. In *Natural Resource Management for Agricultural Production in India*, ed. JSP Yadav, GB Singh, pp. 245–370. New Delhi: Indian Soc. Soil Sci.
55. Kar S, Acharya CL, Parihar SS. 1997. Sustainable soil productivity under rice-wheat system. *Indian Soc. Soil Sci. Bull.* 18, pp. 7–9
56. Mittal S. 2006. *Structural shift in demand for food: projections for 2020*. Work. Pap. 184. Indian Counc. Res. Int. Econ. Relat., New Delhi, 43 pp.
57. Dir. Econ. Stat. 2001. *Agricultural Statistics at a Glance*. New Delhi: Minist. Agric., Gov. India
58. Abbha C, Dadhwal VK. 2005. Estimating spatial, seasonal and temporal variability in terrestrial net primary productivity over India using spot-vegetation data. *Proc. 2nd Int. Veg. User Conf.* Luxembourg: Off. Official Publ. Eur. Comm.
59. Houghton RA, Hackler JL. 2001. *Carbon Flux to the Atmosphere from Land-use Changes: 1850 to 1990*. ORNL/CDIAC-79, NDP-050/R1, Oak Ridge, TN: Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab, US Dep. Energy. **http://cdiac.ornl.gov/epubs/ndp/ndp050/ndp050.html**
60. Nambiar KKM. 1995. Major cropping systems in India. In *Agricultural Sustainability-Economic, Environmental and Statistical Considerations*, ed. V Barnett, R Payne, R Steiner, pp. 133–68. New York: Wiley
61. Sinha SK, Singh GB, Rai M. 1998. *Decline in Crop Productivity in Haryana and Punjab: Myth or Reality?* New Delhi: Indian Counc. Agric. Res. 89 pp.
62. Indian Farmers Fertil. Corp. 2004. *Agricultural Statistics at a Glance*. New Delhi: IFFCO
63. Proj. Dir. Crop. Syst. Res. 2001. *Atlas of Cropping Systems in India*. Modipuram, Meerut, Uttar Pradesh, India. 95 pp.
64. Galloway JN, Cowling EB. 2002. Reactive nitrogen and the world: 200 years of change. *Ambio* 31:64–71
65. Vitousek PM, Hattenschwiler S, Olander L, Allison S. 2002. Nitrogen and nature. *Ambio* 31(2):97–101
66. Prasad R, Rai RK, Sharma SN, Singh S, Shivay YS, Idnani LK. 1998. Nutrient management. In *Fifty Years of Agronomic Research*, ed. RL Yadav, P Singh, R Prasad, IPS Ahlawat, pp. 51–52. New Delhi: Indian Soc. Agron.
67. Bhatt. 2002. *A study on terrestrial nitrogen cycle in India*. PhD thesis. North Gujarat Univ., Patan, India
68. Prasad KV, Badarinath KVS, Yonemura S, Tsuruta H. 2004. Regional inventory of soil surface nitrogen balances in Indian agriculture. *J. Environ. Manag.* 73:209–18
69. Fertil. Assoc. India. 2004. *Fertiliser Statistics 2003–04*, New Delhi: Fertil. Assoc. India
70. Dadhwal VK, Chhabra A. 2002. Landuse/landcover change in Indo-Gangetic plains: cropping pattern and agro-ecosystem carbon cycle. In *Land Use Change Historical Perspectives: Focus on Indo-Gangetic Plains*, ed. YP Abrol, S Sangwan, MK Tiwari, pp. 249–76. New Delhi: Allied
71. Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Adv. Agron.* 87:85–156
72. Dep. Anim. Husb., Dairy. Fish. 2005. *17th Livestock Census Results of India*. New Delhi: Dep. Anim. Husb., Dairy. Fish., Minist. Agric., Gov. India
73. Indira Gandhi Natl. Open Univ. 2004. Environment: agriculture relationships. In *Agriculture and Environment*, pp. 4–50. New Delhi: School Sci.
74. Karnataka Rural Water Supply Sanit. Agency. 2004. *Nitrate Concentration in Ground Water in Karnataka, India*. Karnataka, Bangalore: Rural Dev. Panchayat Raj Dep., Gov. 364 pp.
75. Asian Dev. Bank. 1999. *Asia Least Cost Greenhouse Gas Abatement Strategy—ALGAS*. Manila: Asian Dev. Bank. 260 pp.
76. Tata Energy Res. Inst. 1993. *TERI Energy Data Directory and Yearbook* (TEDDY). New Dehli: TERI. 250 pp.
77. Garg A, Shukla PR, Bhattarcharya S, Dadhwal VK. 2001. Sub-region (district) and sector level SO_2 and NOx emissions for India: assessment of inventories and mitigation flexibility. *Atmos. Environ.* 35:703–13

78. Sharma SK, Kumar V, Singh M. 1992. Effect of different factors on ammonia volatilization losses in soils. *J. Indian Soc. Soil Sci.* 40:251–56
79. Rao EVSP, Puttanna K. 2000. Nitrates, agriculture and environment. *Curr. Sci.* 79(9):1161–68
80. Vittozzi L. 1992. Toxicology of nitrates and nitrites. *Food Addit. Contam.* 9(5):579–85
81. Usha G, Naidu AN, Kamala K. 1993. Dietary intake of nitrate in India. *J. Food Compos. Anal.* 6:242–49
82. Varma GS. 1992. Rain acidification in India caused by nitrates. *Atmosfera* 5:233–39
83. Gupta RS, Naik S, Varadachari VVR. 1989. Environmental pollution in coastal areas of India. In *Ecotoxicology and Climate*, ed. P Bourdeau, JA Haines, W Klein, CR Krishna Murti. Hoboken, NJ: Wiley

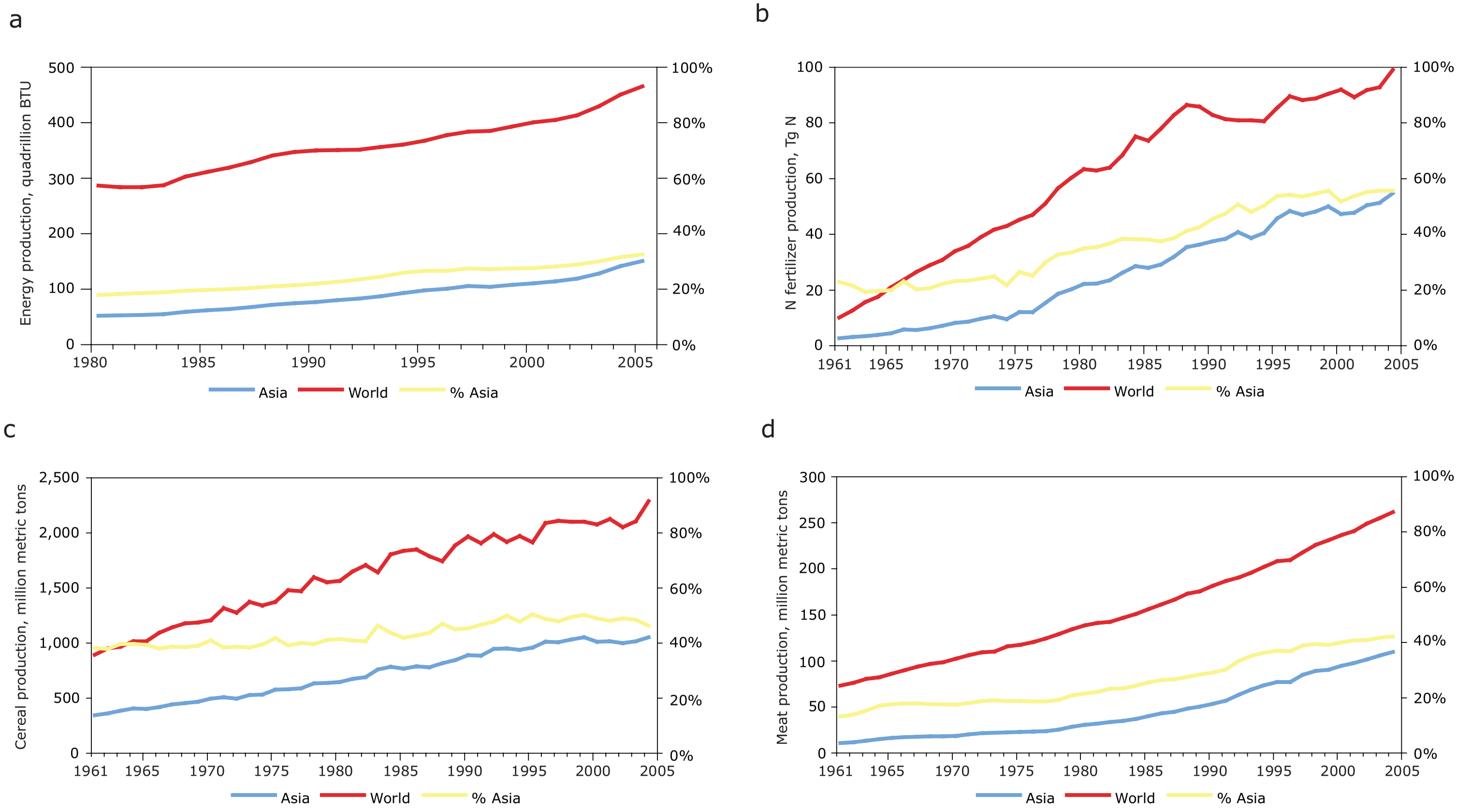
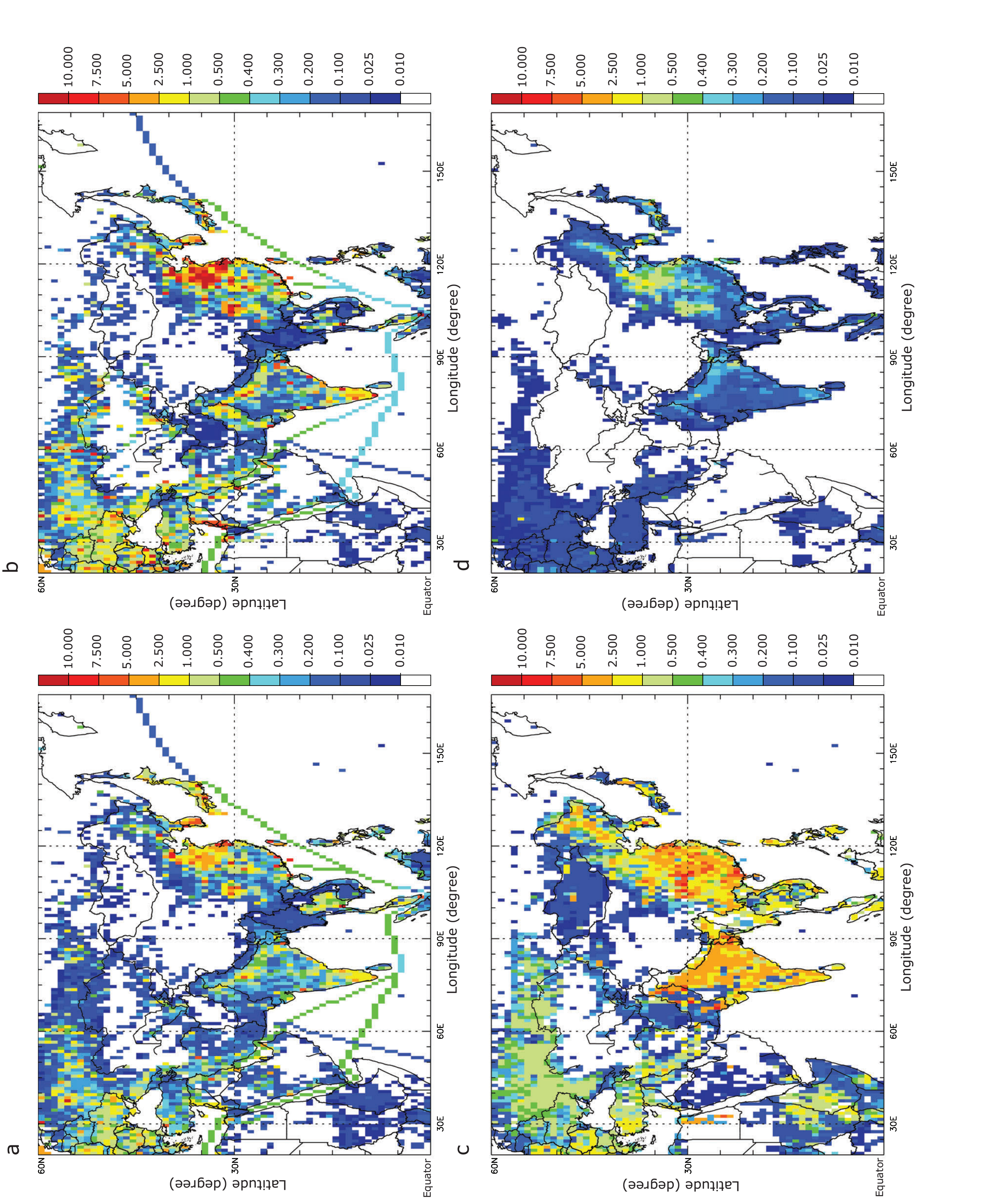


Figure 1

Temporal patterns in production of energy in panel (*a*), fertilizer in panel (*b*), cereal in panel (*c*), and meat in panel (*d*) for Asia and the world, and the percentage contribution from Asia.


a
b
c
d
Latitude (degree)
Longitude (degree)
60N
30N
Equator
30E
60E
90E
120E
150E
10.000
7.500
5.000
2.500
1.000
0.500
0.400
0.300
0.200
0.100
0.025
0.010

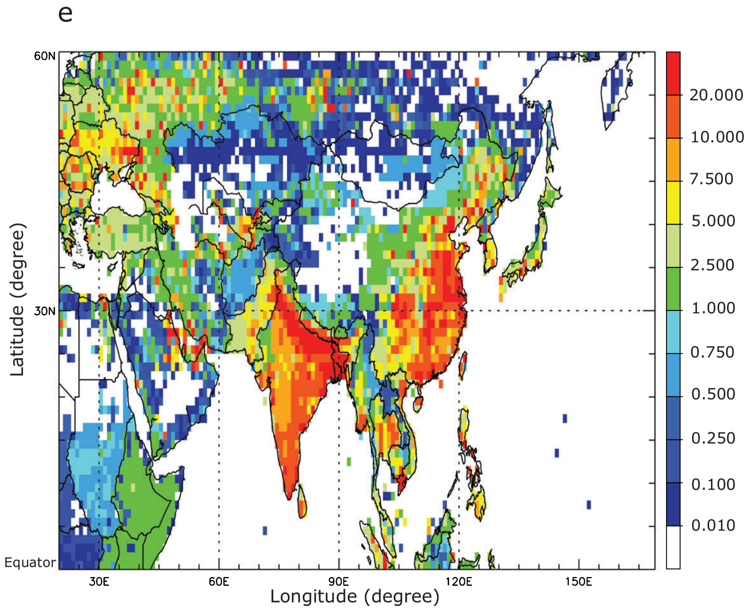
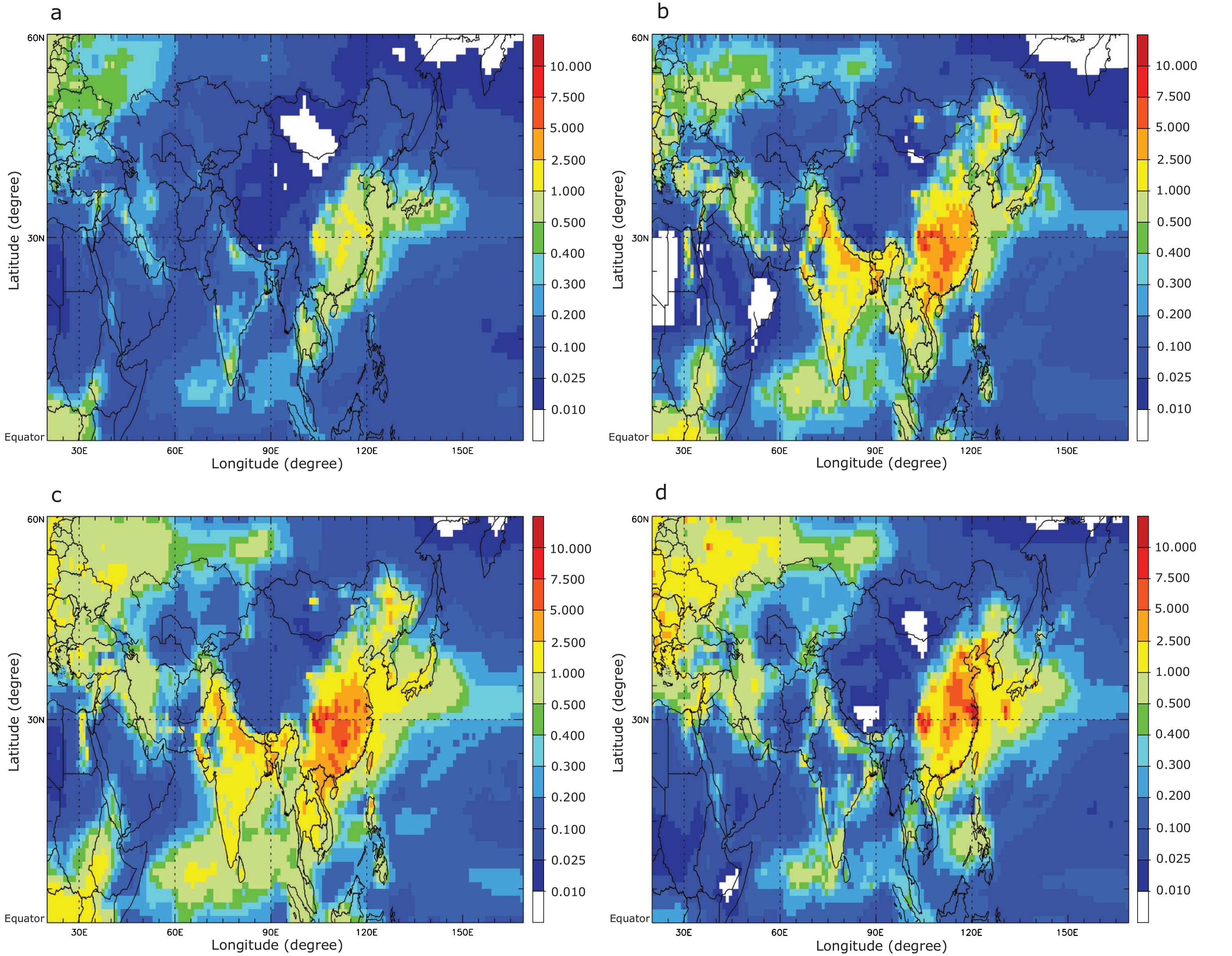


Figure 3

Total annual average anthropogenic emissions of NOx (g N m^{-2} yr^{-1}) in panel (*a*), SO_2 (g S m^{-2} yr^{-1}) in panel (*b*), NH_3 (g N m^{-2} yr^{-1}) in panel (*c*), black carbon (g C m^{-2} yr^{-1}) in panel (*d*), and CH_4 (g C m^{-2} yr^{-1}) in panel (*e*) on a 1° × 1° resolution for 2000 (18, 19).


a
b
c
d
Latitude (degree)
Longitude (degree)
60N
30N
Equator
30E
60E
90E
120E
150E
10.000
7.500
5.000
2.500
1.000
0.500
0.400
0.300
0.200
0.100
0.025
0.010

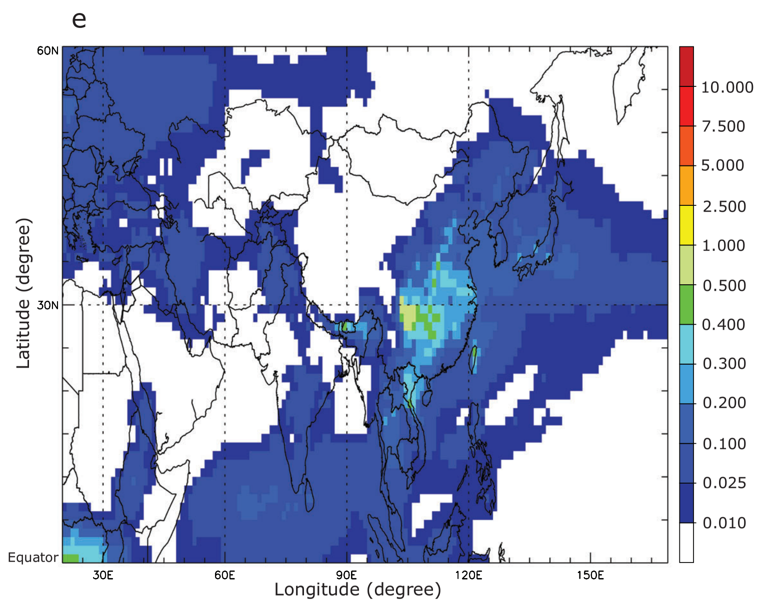
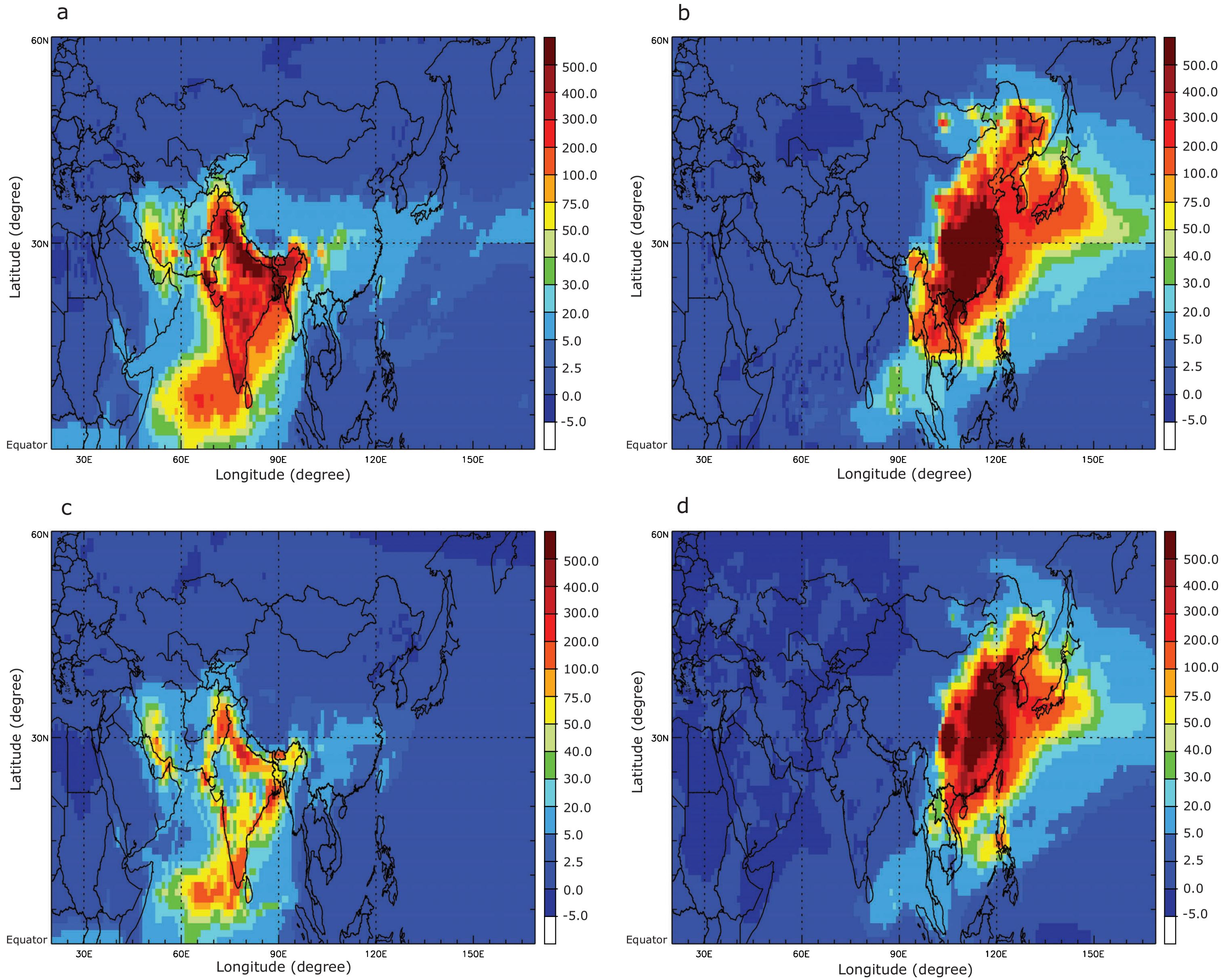


Figure 4

Annual total depositions (wet and dry) of NOy (g N m^{-2} yr^{-1}) in panel (*a*), NHx (g N m^{-2} yr^{-1}) in panel (*b*), total N (NOy + NHx) (g N m^{-2} yr^{-1}) in panel (*c*), total S (SO_4 and SO_2) (g S m^{-2} yr^{-1}) in panel (*d*), and black carbon (g C m^{-2} yr^{-1}) in panel (*e*) in the year 2000 (23, 24).


a
b
c
d
60N
30N
Equator
Latitude (degree)
30E
60E
90E
120E
150E
Longitude (degree)
500.0
400.0
300.0
200.0
100.0
75.0
50.0
40.0
30.0
20.0
5.0
2.5
0.0
-5.0

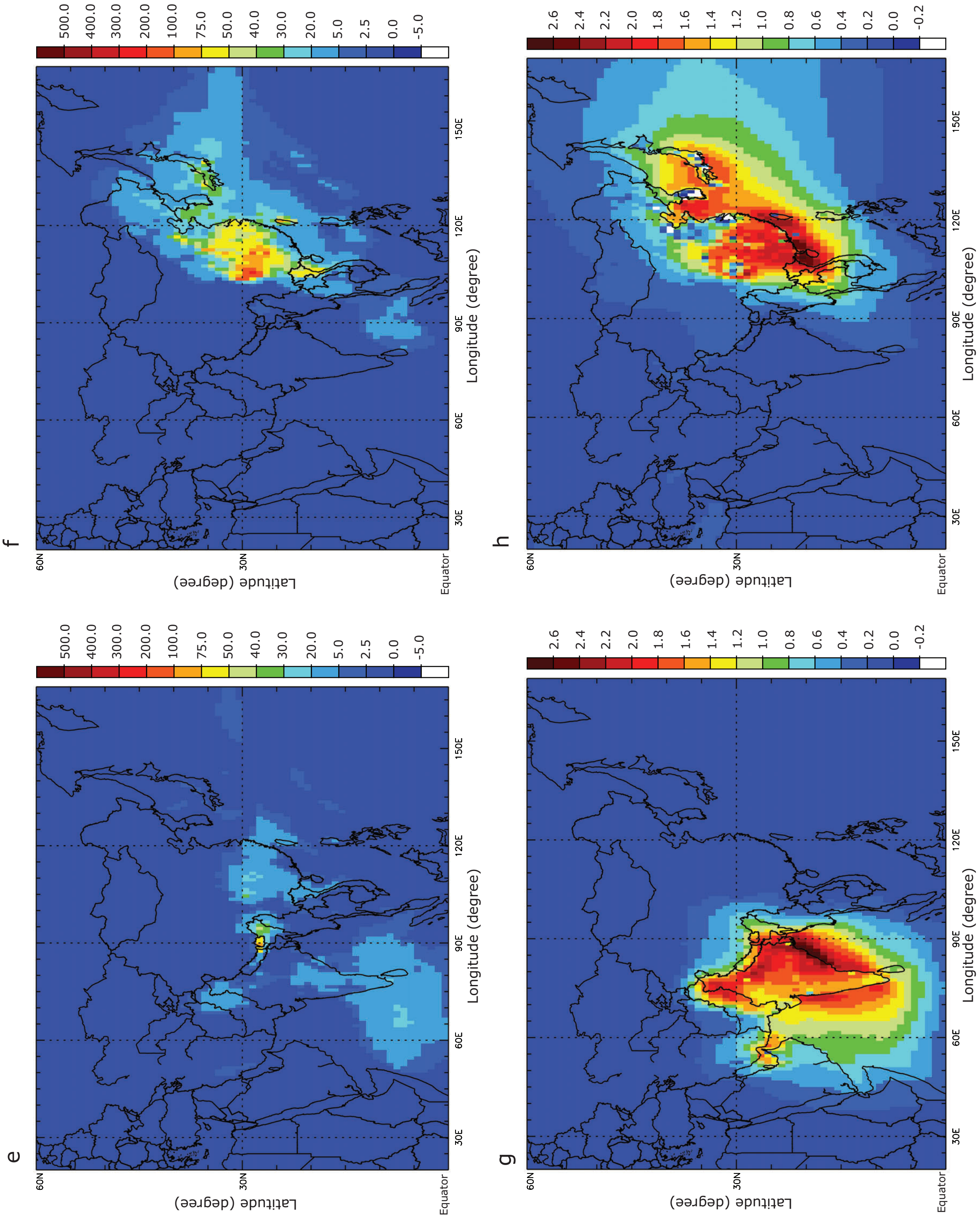
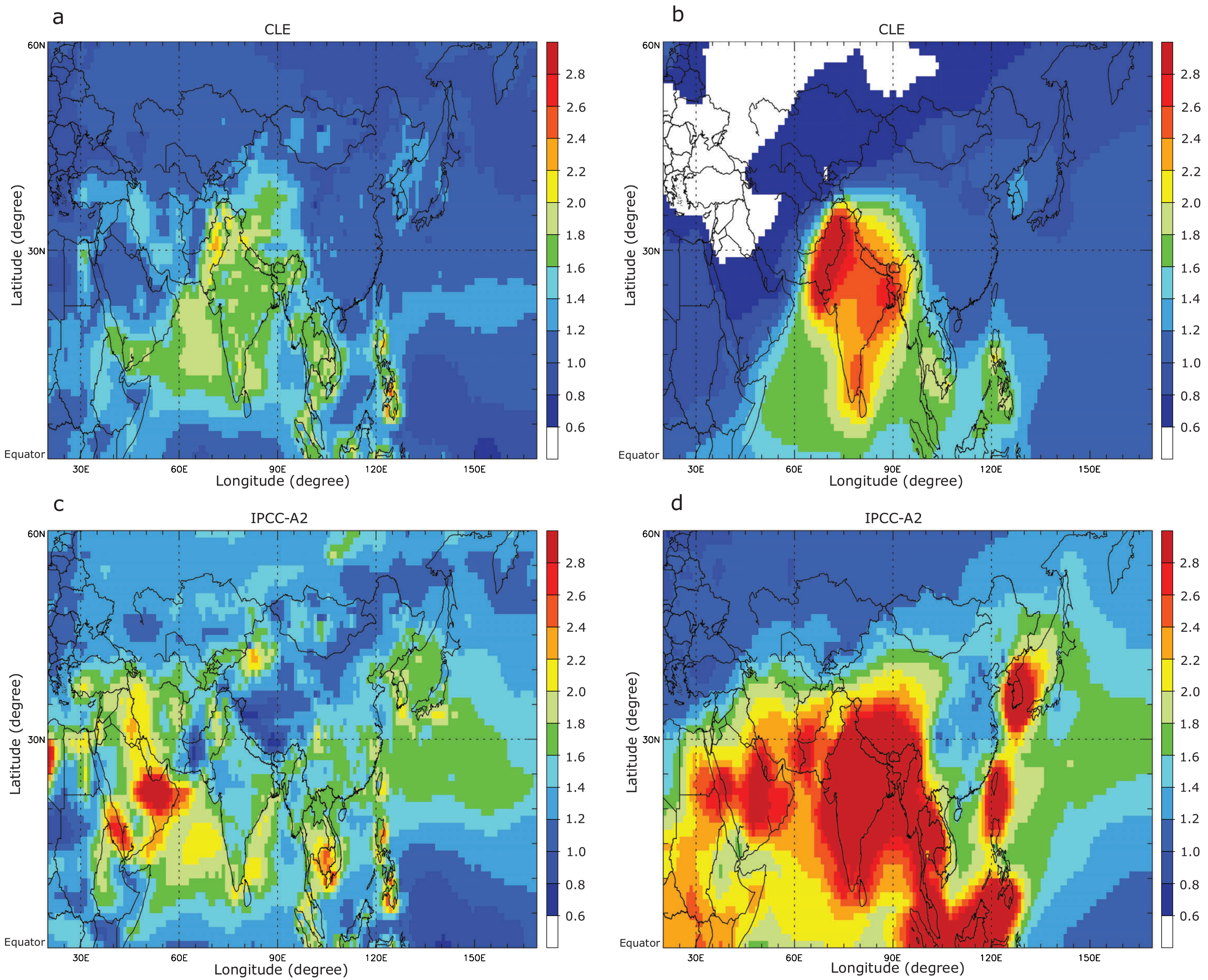

e
f
g
h
Latitude (degree)
Longitude (degree)
60N
30N
Equator
30E
60E
90E
120E
150E
500.0
400.0
300.0
200.0
100.0
75.0
50.0
40.0
30.0
20.0
5.0
2.5
0.0
-5.0
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2

Figure 5

Changes in annual total deposition of nitrogen (mg N m^{-2} yr^{-1}) in panels (*a*,*b*), sulfur (mg S m^{-2} yr^{-1}) in panels (*c*,*d*), and black carbon (mg C m^{-2} yr^{-1}) in panels (*e*,*f*), and annual average surface ozone (O_3) (volume mixing ratios, [nmol/mol]) (*g*,*h*) resulting from a perturbation of 20% in South Asia (*left panels*) and East Asia (*right panels*) (29, 30).

Figure 6

Relative increases in nitrogen (NOy + NHx) in panels (*a*,*c*) and sulfur deposition in panels (*b*,*d*) for the CLE and IPCC-A2 scenarios in 2030 compared to the year 2000 (23, 24).


a
CLE
b
CLE
c
IPCC-A2
d
IPCC-A2
60N
30N
Equator
Latitude (degree)
30E
60E
90E
120E
150E
Longitude (degree)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6

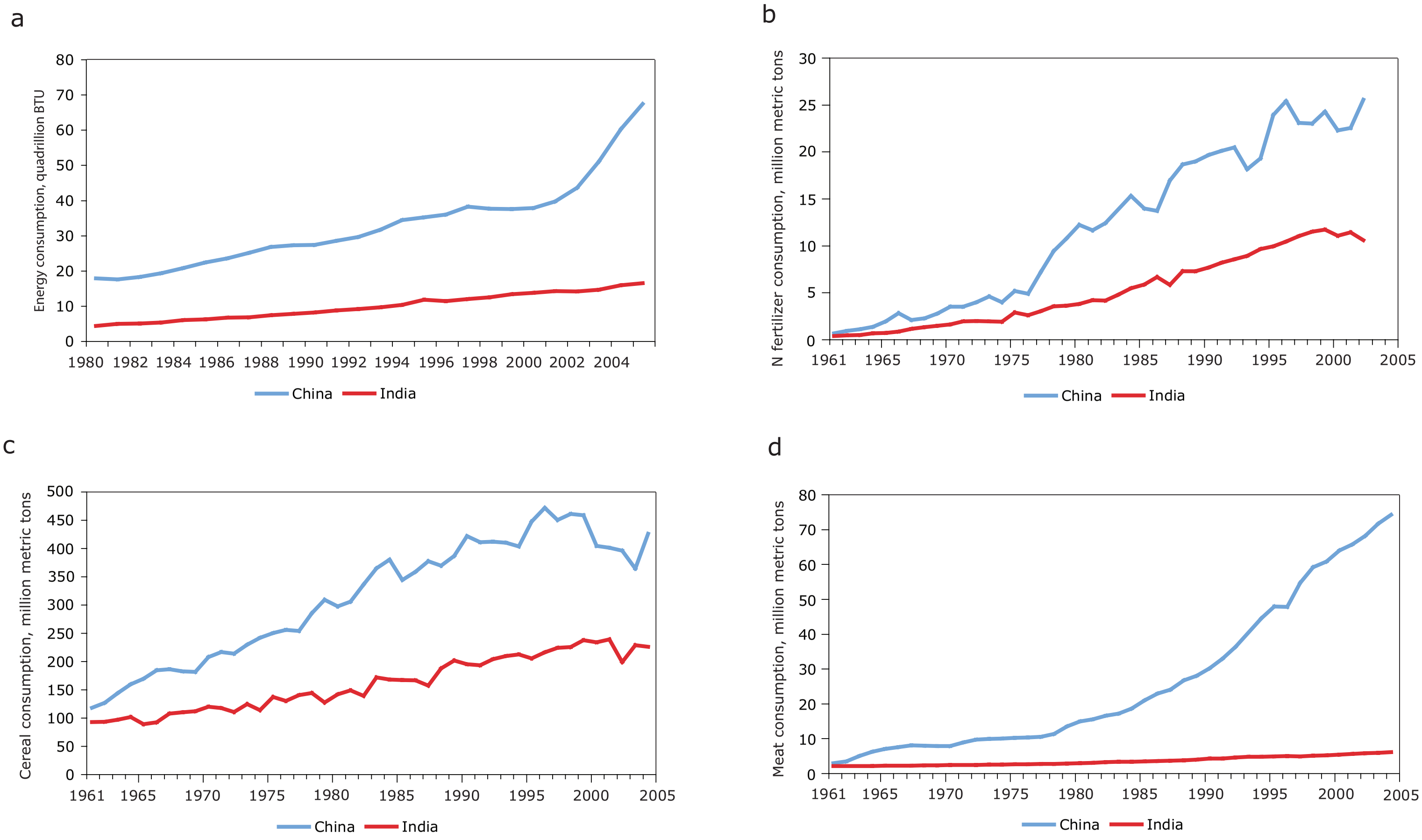


Figure 7

Temporal trends in China and India in the consumption of energy in panel (*a*), N fertilizer in panel (*b*), cereal in panel (*c*) and meat in panel (*d*) (3,4).

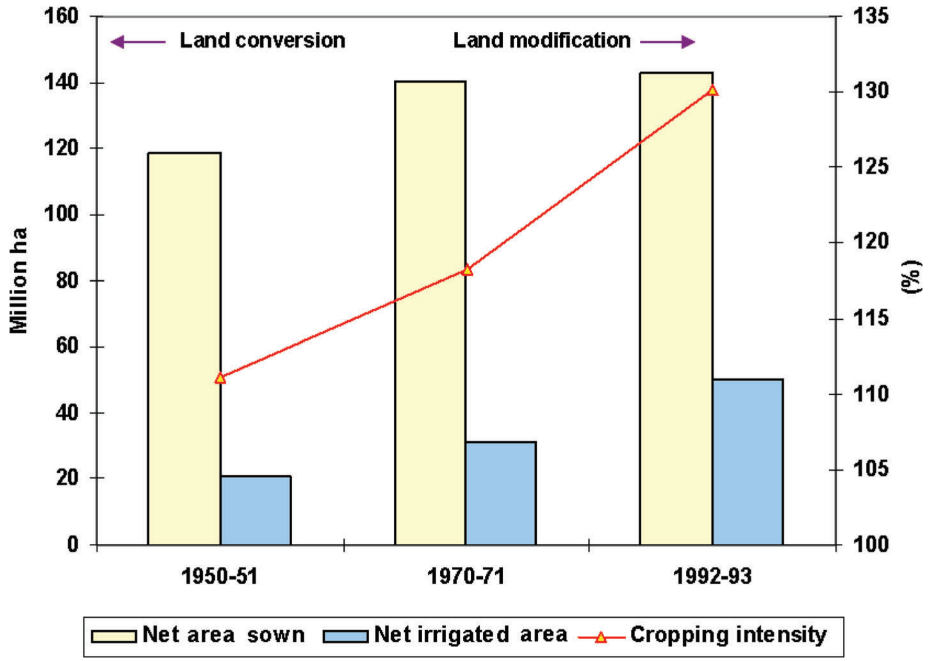


Figure 11

Intensive and extensive transformation of agricultural land use in India (57).

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