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ENVIRONMENTAL SCIENCE

The shape of nitrogen to come

An analysis reveals the huge impact of human activity on the nitrogen cycle in China. With global use of Earth's resources rising per head, the findings call for a re-evaluation of the consumption patterns of developed societies.

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Although Earth's atmosphere consists of nearly 80% dinitrogen (nitrogen gas, N_2), most living organisms cannot use this form of the element and require it to be converted into usable forms, such as ammonia. Humans have long exploited the ability of leguminous crops to fix dinitrogen into usable reactive nitrogen compounds, improving soil fertility. But the amount of reactive nitrogen produced in this way is now greatly exceeded by that produced industrially[1]. Together with nitrogen oxides, another form of reactive nitrogen produced as a by-product of combustion processes, nitrogen compounds released into the environment by human activity are weaving a web of unforeseen consequences. In a paper published on *Nature*'s website today, Liu *et al.*[2] quantify the massive scale of these changes to the nitrogen cycle across China, which are a direct result of increases in human activities such as food production, travel and energy consumption.

In a study remarkable for the scale of its achievement, Liu *et al.* have shown how increases in the rate of the release to the atmosphere of nitrogen oxides (NO_x) and ammonia (NH_3) have been matched by increases in the amounts of atmospheric reactive nitrogen (N_r) deposition, measured in precipitation. To do this, they drew on more than 300 published data sets of N_r deposition from across China spanning 30 years (from 1980 to 2010). Most importantly, the authors went on to show how nitrogen uptake by plants and its levels in leaves have changed across China as a consequence.

The focus of the study was to provide quantified evidence of biogeochemical and biological change, but Liu and colleagues' results can also be considered as indicators of a pan-dimensional modification to the nitrogen cycle. The components of this modification include: the formation of nitrogen-containing fine particulate matter in air, which poses a substantial threat to human health; the contribution of NO_x to the formation of ground-level ozone, which causes crop losses; increased emissions of nitrous oxide (N_2O), a greenhouse gas; and extreme levels of water pollution by nitrates and other forms of N_r (refs 3–5). Concern over water pollution was highlighted during the 2008 Beijing Olympics, when a massive algal 'green tide' severely disrupted training for sailing events.

Liu *et al.* report a 60% increase in atmospheric N_r deposition in China since 1980. However, their results are based on the amount of N_r sampled by open rain collectors, and, as the authors recognize, the total amount deposited will be several times larger. For example, most rain is captured by these samplers, but snowfall is only partially caught. N_r-containing gases, fine particles and fog are also caught, but the amount of N_r captured from these components is much less than that deposited on plant canopies. The total annual N_r deposition to Chinese ecosystems will therefore often be more than 80 kilograms of nitrogen per hectare — several times larger than the rain-collector data***[OK?]***.

To assess the effects of increased nitrogen deposition on vegetation, the researchers drew on data from crop-fertilizer trials, which typically include control measurements of crop production without fertilizer. By combining data from sites across China, they estimate that a 15% increase in nitrogen uptake by plants has

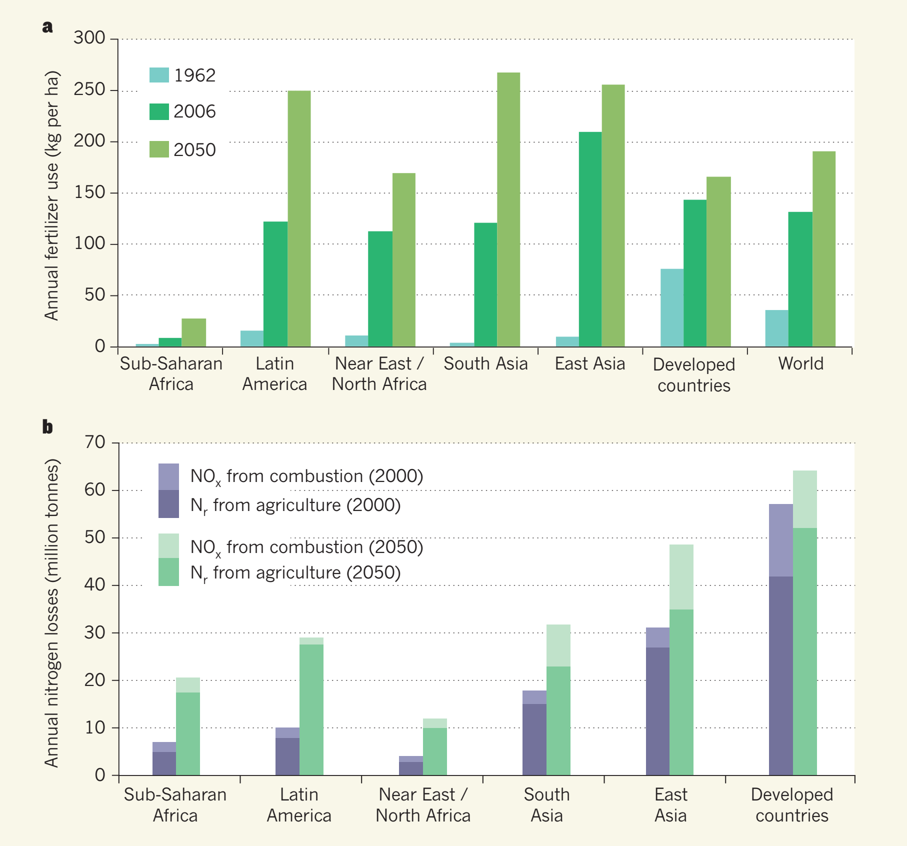

Figure 1 | Fertilizer use and nitrogen losses to the environment. **a**, Estimated and projected global fertilizer use[7] for fertilizers that contain nitrogen, phosphorus and potassium compounds. **b**, Total estimated losses to the environment of nitrogen oxides (NO_x) in emissions from combustion sources and of reactive nitrogen (N_r) from agricultural activities for 2000 and 2050. Estimates of NO_x for 2050 are the mean of the A1 and A2 emission scenarios[9] (originally developed for the Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios); estimates of N_r are the mean of the Global Orchestration and Technogarden scenarios of the Millenium Ecosystem Assessment[8].

occurred since 1980 (see Fig. 3b of the paper[2]). In principle, the additional N_r inputs resulting from NO_x emissions could have increased crop productivity. However, the authors did not report the net change in crop growth, which leaves open the question of whether the fertilization effect provided by increased N_r deposition outweighs the growth-reduction effect of NO_x-related ground-level ozone. For natural ecosystems, the extra nutrients remain a major threat to biological diversity[6].

Rates of nitrogen fertilization in China are among the highest in the world — fostered by the country's subsidy of fertilizer manufacturing, which was established to address food-security concerns. However, this reliance on fertilizers has decreased the extent to which nitrogen from manure and sewage is recycled, reducing the efficiency of nitrogen use overall. Fertilizer use in China can be compared with estimates of regional and global rates of total fertilization[7] (which includes fertilizers containing nitrogen, phosphorus and potassium compounds; Fig. 1a) from the United Nations Food and Agriculture Organization (FAO). In the 1960s, fertilizer inputs were largest in developed countries, at 75 kg per ha. By 2006, East Asia (including China) had taken the lead, with average inputs at around 200 kg per ha, and local values often five times higher. Liu *et al*. show how this has combined with a 3.2-fold increase in livestock and a 20.8-fold increase in vehicles since 1980, together leading to substantial increases in N_r pollution in China.

It must be emphasized, however, that nitrogen is not only a problem in China. The FAO estimates suggest that there will be a further 50% increase in global fertilizer consumption by 2050 as a result of trends in population, improved diets and increased consumption of animal products. At the same time, projections based on scenarios that emphasize population and economic growth[8,9] suggest a global increase in nitrogen losses to the wider environment of 70% by 2050 (Fig. 1b). By 2050, estimates[7] suggest that average fertilizer inputs in Latin America and South Asia will approach Chinese levels, and major increases will also occur in North Africa and the Near East.

Regional increases in N_r losses are broadly similar and projections indicate a substantial worsening of nitrogen-pollution effects, including increased NO_x emissions in Asia, unless action is taken. In fact, these projections may be conservative. If the current trends reported by Liu *et al*. are extrapolated, an 85% increase in NH_3 and a 200–240% increase in NO_x emissions in China is possible by 2050.

Liu and colleagues' data and the projections shown in Figure 1 highlight the urgency for global action to tackle increasing nitrogen levels. But there is still no global international convention that defines targets for better management of global nitrogen and nutrient cycles, as highlighted in a recent report[10]. The authors of that report (who include ourselves) have proposed a shared aspirational goal to improve nitrogen-use efficiency by 20% by the year 2020; a cost-benefit calculation suggests that this would provide net savings equivalent to around US$170 billion. This will require changes in industrial and agricultural practices, and a re-evaluation of the consumption patterns of Western society. But achieving all of this will require countries to get organized, and to start taking the nitrogen challenge seriously. ■

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1. Galloway, J. N. *et al. Science* **320,** 889–892 (2008).
2. Liu, X. *et al. Nature* http://dx.doi.org/10.1038/nature11917 (2013).
3. Sutton, M. A. *et al*. in *The European Nitrogen Assessment* (eds Sutton, M. A. *et al*.) xxiv–li (Cambridge Univ. Press, 2011).
4. Suddick, E. C., Whitney, P., Townsend, A. R. & Davidson, E. A. *Biogeochemisty* http://dx.doi.org/10.1007/s10533-012-9795-z (2012).
5. Kim, T. W., Lee, K., Najjar, R. G., Jeong, H. D. & Jeong, H. J. *Science* **334,** 505–509 (2011).
6. Bleeker, A., Hicks, K., Dentener, F., Galloway, J. & Erisman, J. W. *Environ. Pollut.* **159,** 2280–2288 (2011).
7. Alexandratos, N. & Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision* (FAO, 2012).
8. Bodirsky, B. L. *et al*. *Biogeosciences* **9,** 4169–4197 (2012).
9. Alcamo, J. *et al*. in *Ecosystems and Human Well-being* Vol. 2 (eds Carpenter, S. R., Pingali, P. L., Bennett, E. M. & Zurek, M. B.) 297–373 (Island, 2005).
10. Sutton, M. A. *et al*. *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution* Ch. 8, 95–108 (Centre for Ecology and Hydrology, 2013).