James A. Baker III Institute for Public Policy
Rice University

Reducing Nitrogen Fertilizer Use to Mitigate Negative Environmental Impact in China

By

Yao Huang

State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry (LAPC),
Institute of Atmospheric Physics, Chinese Academy of Sciences; and
College of Resources and Environmental Sciences, Nanjing Agricultural University

Ronald L. Sass

James A. Baker III Institute for Public Policy, Rice University

Wenjuan Sun, Wen Zhang, and Yongqiang Yu

LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences

December 22, 2010

China needs to take action now to mitigate the serious environmental problems caused by the overuse of synthetic nitrogen fertilizer

Although agriculture in China utilizes only 7% of the world's arable land area, it feeds some 22% of the global population. Substantial growth in the use of synthetic nitrogen (N) fertilizer in China since the 1970s has provided significant economic and social benefits, including higher farm incomes, improved food consumption, and the maintenance of national food security. China, now the largest consumer of synthetic N in the world, accounts for 32% of the world's total consumption (1). Nitrogen input is essential for high crop yields, but an excess use of N fertilizer cannot promise a substantial increase in crop productivity. Too much N fertilizer results in diminishing crop returns (2) and leads to diminished environmental quality and human well-being (3–5). Overuse of synthetic nitrogen fertilizer has become widespread across China, resulting in severe environmental problems. If the excessive application of nitrogen fertilizer is not brought under control, China's environment will continue to deteriorate.

Overuse of synthetic nitrogen fertilizer

In 2007, cereals yield (rice, wheat, and maize) in China contributed 21.8% of the global total (6), but synthetic N fertilizer used in cereal production represented 30.3% of world total (1). Current usage of N per unit crop area in China is higher, but cereal yields are lower than in the United States, Western Europe, and the neighboring Republic of Korea (see Table 1) (7). Over the period 1987-2007, while increased input of synthetic N has improved the per-hectare cereals yield in China, the ratio of cereals yield per unit of applied N fertilizer (called the partial factor productivity for N fertilizer, or PFP_N) has decreased, thus resulting in a lower nitrogen use efficiency. In contrast, the PFP_N in the Republic of Korea, the United States, and Western Europe have all increased, and are currently much higher than in China (see Table 1) (7).

Table 1.

N use, cereals yield and PFP_N	Mean and trend	China	Republic of Korea	USA	Western Europe
Synthetic N rate in cereals	Mean of 1987-91 (kg ha^{-1})	100	130	108	168
	Mean of 2003-07 (kg ha^{-1})	178	90	133	146
	Trend in 1987-2007 (kg ha^{-1} $year^{-1}$)	4.8***	-2.6***	1.6***	-1.3***
Cereals yield	Mean of 1987-91 (t ha^{-1})	4.1	5.9	4.4	5.8
	Mean of 2003-07 (t ha^{-1})	5.2	6.2	6.5	6.7
	Trend in 1987-2007 (kg ha^{-1} $year^{-1}$)	65***	27*	123***	65***
PFP_N	Mean of 1987-91 (kg grain kg^{-1} N)	41	36	41	34
	Mean of 2003-07 (kg grain kg^{-1} N)	29	56	49	46
	Trend in 1987-2007 (kg grain kg^{-1} N $year^{-1}$)	-0.8***	1.3*	0.4***	0.7***

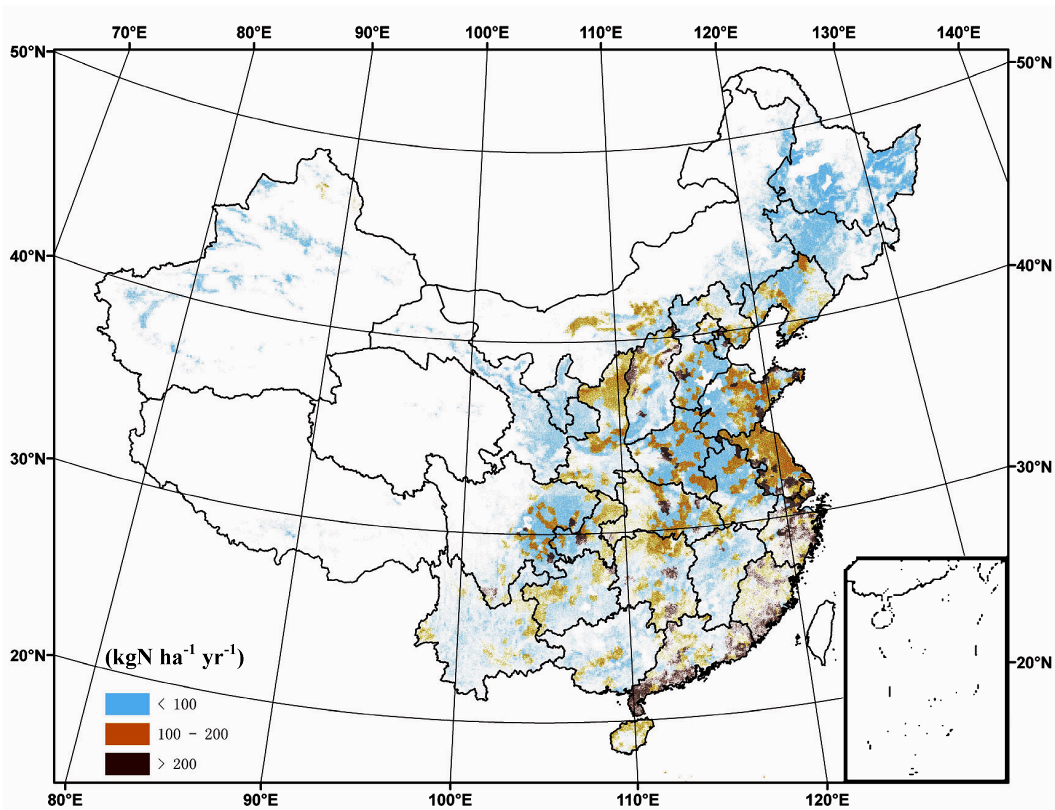
Mean value and trends in synthetic nitrogen use, cereals yield, and partial factor productivity (PFP_N) in China, Republic of Korea, United States, and Western Europe (7). Over the period 1987-2007, cereals yield in the Republic of Korea and Western Europe have gone up in spite of N fertilizer cuts; the annual increment of synthetic N in China was three times (4.8 kg ha^{-1} $year^{-1}$) that of the United States, but the increment of cereals yield (65 kg ha^{-1} $year^{-1}$) was only one-half.

Low nitrogen use efficiency (NUE) was reported in a vast area across China (9, 10). The main cause of the low NUE is the widespread overuse of nitrogen. A more recent study indicated that the mean value of synthetic nitrogen use efficiency in cereal crops (rice, wheat, and maize) in China is only approximately 30%. This value is less than the global average of 33%—

comparable to an average value of 29% found in developing countries but considerably lower than the average value of 42% in developed countries (11).

Most of the cereal crop harvest area of China is located in eastern, central, and southern parts of the country (see Figure 1) (12). NUE values lower than 30%, primarily due to a significant overuse of synthetic N, account for approximately 47% of the total country harvest area of these three cereal crops.

Figure 1.



Estimated overuse of synthetic N in cereal crops across China (12)

Environmental problems associated with nitrogen fertilizer use

Fertilizer N is lost due to gaseous plant emission, soil nitrification and denitrification, volatilization, surface runoff, and leaching. Much of this loss is as the gases nitrous oxide (N_2O), nitric oxide (NO), and ammonia (NH_3) emitted to the atmosphere. Of increasing concern is N_2O

due to its potent impact on global warming. It is 298 times more powerful than carbon dioxide (CO_2) in terms of global warming potential. Of global anthropogenic missions in 2005, agriculture accounts for about 60% of N_2O (13). Given the 32% share of global N consumption in China, the synthetic fertilizer N-induced N_2O emissions may amount to as much as one-third of the world total. Moreover, the production and distribution of synthetic fertilizer N results in the additional release of CO_2 in an amount roughly equivalent to that of the direct emission of N_2O (in terms of global warming potential) (10).

Overuse of N fertilizer has already induced significant acidification in major Chinese croplands. From the 1980s to the 2000s, soil pH has declined across China by from 0.13 to 0.80 pH units with the anthropogenic acidification driven by N fertilization 10 to 100 times greater than that associated with acid rain (14). Soil acidity associated with aluminum toxicity and low contents of exchangeable basic cations usually limits crop yields (15). Thus the acidification of soils from the use of excessive levels of N fertilization will no doubt negatively impact future sustainable crop production in China.

Excessive use of synthetic N has resulted in higher atmospheric N deposition and in higher N in agricultural runoff. There are now large regions of China where the N deposition rates range from 10 to 60 kgN ha^{-1} $year^{-1}$ (16). This is significantly greater than the global average of 3.5 kgN ha^{-1} $year^{-1}$ (17). Nitrogen deposition, together with agricultural runoff, increases nutrients in water bodies, resulting in eutrophication and harmful algal blooms. Taihu, the third largest freshwater lake in China, serves as a critical source for drinking water and agricultural irrigation as well as for fishery and recreational needs. In early June 2007, a bloom of cyanobacteria fanned out across Taihu (18), leading to a drinking water crisis for millions of people. The eruption of this bloom in Taihu is mainly attributable to high atmospheric N deposition and agricultural runoff (18, 19). Blooms in the Yellow Sea of China, which have escalated in frequency over the past several decades, have also been related to atmospheric deposition (20).

The primary anthropogenic N source in groundwater is leaching from agroecosystems, although in some regions human waste disposal can also be important. Nitrite levels in groundwater are often high in China (21, 22) and are generally correlated with the rate of use of nitrogen fertilizer (23).

The overuse of N fertilizer inevitably leads to an increased risk to public health. Nitrate content in ground and drinking water found in 37 of 69 locations covering an area of about 140,000 square kilometers in northern China (24), and in 46% of 600 groundwater samples taken in the provinces of Shanxi, Hebei, Shandong, Tianjin, and Beijing (25) exceeded the World Health Organization (WHO) limit for nitrate content in drinking water of 50 mg per liter. Public health agencies have long recognized that excessive nitrate in water can sometimes lead to a fatal condition in infants (26). Nitrosamines, which are produced from nitrites and associated with various human cancers (27), have also been observed in ground and drinking water samples (28).

There is evidence that increases in synthetic N fertilizer use reduce plant resistance to insect pests (29) and tend to enhance insect pest populations. The increases in populations of major insect pests in most of the rice growing areas in Asia are closely related to the excessive application of nitrogen fertilizers (30). A range of crop pathogens, including fungi, bacteria, and viruses, also cause more severe damage when N inputs are high (31). The cropland area exposed to diseases and pests infestations in China increased from ~230 million hectares (Mha) year^{-1} in the early 1990s to ~345 Mha year^{-1} in the mid-2000s, although this trend cannot be attributed to excessive application of nitrogen fertilizers alone. Annual application of pesticides increased from ~0.77 million tons in 1991 to 1.62 million tons in 2007. Consequently, pesticide resistance has become a ubiquitous problem, as have the environmental and human health threats associated with pesticide transfers to air, water, and soil.

Take action against the overuse, no time to delay

It is well recognized that nitrogen use efficiency can be improved by matching temporal and spatial N supply with plant demand, applying N fertilizer at or near the plant roots, balancing nitrogen, phosphorus, and potassium fertilizer application, and using nitrification inhibitors and controlled release N fertilizers. On a national scale, improving NUE in cereals crops (rice, wheat, and maize) by 1% could reduce by 220,000 tons the synthetic N used per year. Improving NUE to 40% is expected to cut 4.4 million tons of synthetic N used per year, accounting for 27% of the total fertilizer used (10).

Chinese scientists have made considerable progress in devising improved N management practices to limit N overuse, but uptake by farmers has been limited by technical, institutional, and socioeconomic factors. For example, many young farmers now leave the countryside for construction or factory jobs in the city after sowing their fields. That means they don't have time to apply nitrogen in multiple doses. Other farmers are simply unwilling to risk cutting back fertilizer use for fear of reducing crop yield (32). Another reason some farmers overuse N fertilizer is because they simply lack knowledge about nutrient management and environment protection.

Overuse of synthetic N fertilizers used to be common practice in many developed countries, but this situation has been improved. In the United Kingdom, for example, the overuse of synthetic N fertilizers was widespread in the 1970s and early 1980s, with serious environmental consequences. Since then, policy and regulatory changes have brought about improvements in nutrient management and agricultural technology that have resulted in stable or decreasing rates of synthetic nitrogen fertilizer use, while cereals yields have gone up (32) (see Table 1, Western Europe, above). Clearly, China now has a chance to follow the same path as the United Kingdom and other developed countries.

Reducing N fertilizer use is urgent in order to mitigate the risk of environmental pollution and human health threats in China. This could be accomplished through stringent policies of fertilizer regulation, recommendations of improved N management practices for the farmers, training and education of farmers on nutrient management, and public awareness of environment protection. China needs to take action. There is no time to delay.

References and Notes

1. P. Heffer, "Assessment of Fertilizer Use by Crop at the Global Level 2006/07–2007/08," (International Fertilizer Industry Association, Paris, France, 2009, 8-11.
2. D. Tilman, K.G. Cassman, P.A. Matson, R. Naylor, S. Polasky, "Agricultural sustainability and intensive production practices," *Nature* 418, (2002) 671.
3. P. A. Matson, R. Naylor, I. Ortiz-Monasterio, P. A. Matson, R. Naylor, I. Ortiz-Monasterio, "Integration of Environmental, Agronomic, and Economic Aspects of Fertilizer Management," *Science* 280, (1998) 112.
4. J.N. Galloway et al., "The Nitrogen Cascade," *Bioscience* 53 (2003): 341.
5. J. Liu and J. Diamond, "China's environment in a globalizing world," *Nature* 435 (2005): 1179.
6. United Nations Food and Agricultural Organization, http:// faostat.fao.org/ (2009).
7. Synthetic N rate in cereals was derived from total consumption of N (8), the share of cereals (1), and the harvest area of cereals (6). Data of cereals yield come from United Nations Food and Agricultural Organization (6). Trends in synthetic N rate, cereals yield, and PFP_N are the slopes of linear regression against time over 1987-2007. *, **, and *** represent statistical significant at probability levels of 0.05, 0.01, and 0.001, respectively.
8. International Fertilizer Industry Association, http://www.fertilizer.org/ifa/ifadata/ (2009).
9. X.T. Ju et al., "Reducing environmental risk by improving N management in intensive Chinese agricultural systems," *Proc. Natl. Acad. Sci. U.S.A*. 106 (2009): 3041.
10. Y. Huang and Y. Tang, "An estimate of greenhouse gas (N_2O and CO_2) mitigation potential under various scenarios of nitrogen use efficiency in Chinese croplands," *Global Change Biol*. 16 (2010): 2958.
11. W.R. Raun and G.V. Johnson, "Improving Nitrogen Use Efficiency for Cereal Production," *Agron. J*. 91 (1999): 357.

12. We firstly estimated synthetic nitrogen use efficiency (NUE, %) on the basis of crop N removal, indigenous N supply, and synthetic N application at a county level. Overuse of synthetic N (ΔN, kg N ha^{-1}) in each county was then estimated under a NUE scenario of 40% by $\Delta N = N \times (40 - NUE)/40$, $\Delta N = 0$ for NUE>40%. N is synthetic nitrogen rate (kg N ha^{-1}). For details, see ref (10).

13. P. Smith et al., "Agriculture," in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer, eds. (Cambridge, UK and New York: Cambridge University Press, 2007), 498-540.
14. J.H. Guo et al., "Significant Acidification in Major Chinese Croplands" http://www.sciencemag.org/search?author1=J.+H.+Guo&sortspec=date&submit=SubmitScience 327 (2010): 1008.
15. D.F. Garvin and B.F. Carver, "Role of the genotype in tolerance to acidity and aluminum toxicity," in *Handbook of Soil Acidity*, Z. Rengel, ed. (New York: Marcel Dekker Inc., 2003): 387-406.
16. C. Lü and H. Tian, "Spatial and temporal patterns of nitrogen deposition in China: Synthesis of observational data." *J. Geophys. Res.* 112 (2007).
17. G.K. Phoenix et al., "Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts." *Global Change Biol.* 12 (2006): 470.
18. L. Guo, "Doing Battle With the Green Monster of Taihu Lake," *Science* 317 (2007): 1166.
19. S. Zhai, L. Yang and W. Hu, "Observations of atmospheric nitrogen and phosphorus deposition during the period of algal bloom formation in northern Lake Taihu." China *Environ. Manage*. 44 (2009): 542.
20. D.M. Anderson, P.M. Glibert, and J.A.M Burkholder, "Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences." *Estuaries* 25(4b) (2002): 704.
21. J. Chen, C. Tang, Y. Sakura, J. Yu, and Y. Fukushima, "Nitrate pollution from agriculture in different hydrogeological zones of the regional groundwater flow system in the North China Plain." *Hydrogeology J*. 13 (2005): 481.

22. X. Li, C. Hu, J. A. Delgado, Y. Zhang, and Z. Ouyang, "Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in north China plain," *Water Manage*, 89 (2007): 137.
23. C. Zhao et al., "A lysimeter study of nitrate leaching and optimum nitrogen application rates for intensively irrigated vegetable production systems in Central China," *J. Soils Sediments* 10 (2010): 9.
24. W.L. Zhang, Z.X. Tian, N. Zhang, and X.Q. Li, "Nitrate pollution of groundwater in northern China," *Agr. Ecosyst. Environ*. 59 (1996): 223.
25. X.T. Ju, X.J. Liu, F.S. Zhang, and M. Roelcke, "Nitrogen Fertilization, Soil Nitrate Accumulation, and Policy Recommendations in Several Agricultural Regions of China," *Ambio* 33 (2004): 300.
26. L. Knobeloch, B. Saina, A. Hogan, J. Postle, and H. Anderson, "Blue babies and nitrate-contaminated well water," *Environ. Health. Perspec*. 108 (2000): 675.
27. J.R. Follett and R.F. Follett, "Utilization and Metabolism of Nitrogen by Humans" in *Nitrogen in the Environment: Sources, Problems, and Management*, R.F. Follett, J.L. Hatfield, eds. (Amsterdam, Netherlands: Elsevier Science, 2001), 65-92.
28. N.F. Liu, J. Tang, and H.S. Mohamed Ismael, "Study on environmental etiology of high incidence areas of liver cancer in China," *World J. Gastroentero.* 6 (2000): 572.
29. M.A. Altieri and C.I. Nicholls, "Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems," *Soil Till. Res*. 72 (2003): 203.
30. Z.X. Lu, X.P. Yu, K.L. Heong, and C. Hu, "Effects of nitrogen fertilizer on herbivores and its stimulation on major pests in rice," *Rice Science* 14 (2007): 56.
31. D.M. Huber, "The use of fertilizers and organic amendments in control of plant disease," in *CRC Handbook of Pest Management in Agriculture*, D. Pimentel, ed. (Boca Raton, FL: CRC Press, 1981), 357-394.
32. M. Hvistendahl, "China's Push to Add by Subtracting Fertilizer." *Science* 327 (2010): 801.