New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China

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Synthetic nitrogen (N) fertilizer has played a key role in enhancing food production and keeping half of the world's population adequately fed. However, decades of N fertilizer overuse in many parts of the world have contributed to soil, water, and air pollution; reducing excessive N losses and emissions is a central environmental challenge in the 21st century. China's participation is essential to global efforts in reducing N-related greenhouse gas (GHG) emissions because China is the largest producer and consumer of fertilizer N. To evaluate the impact of China's use of N fertilizer, we quantify the carbon footprint of China's N fertilizer production and consumption chain using life cycle analysis. For every ton of N fertilizer manufactured and used, 13.5 tons of CO_2-equivalent (eq) (t CO_2-eq) is emitted, compared with 9.7 t CO_2-eq in Europe. Emissions in China tripled from 1980 [131 terrogram (Tg) of CO_2-eq (Tg CO_2-eq)] to 2010 (452 Tg CO_2-eq). N fertilizer-related emissions constitute about 7% of GHG emissions from the entire Chinese economy and exceed soil carbon gain resulting from N fertilizer use by several-fold. We identified potential emission reductions by comparing prevailing technologies and management practices in China with more advanced options worldwide. Mitigation opportunities include improving methane recovery during coal mining, enhancing energy efficiency in fertilizer manufacture, and minimizing N overuse in field-level crop production. We find that use of advanced technologies could cut N fertilizer-related emissions by 20–63%, amounting to 102–357 Tg CO_2-eq annually. Such reduction would decrease China's total GHG emissions by 2–6%, which is significant on a global scale.

carbon accounting | life cycle assessment | food security | policy

The Haber–Bosch process is one of the greatest inventions in modern human history. It enables industrial-scale production of ammonia from atmospheric N_2 using energy. From ammonia, various synthetic nitrogen (N) fertilizers are manufactured, without which nearly half of the world's population would not be alive today (1). However, synthetic N fertilizer has become "too much of a good thing" because much of the N applied to cropland escapes the agricultural system and becomes a pollutant, which disrupts terrestrial and aquatic ecosystem functions and contributes to global climate change. The environmental cost is considerable, between €70 billion and €320 billion per year just for the European Union according to a recent 5-y European nitrogen assessment (2). This 200-member expert panel considered N emission reductions a central environmental challenge in the 21st century and called for a global interconvention N protocol to address the issue. Indeed, coordinated global efforts are particularly critical when dealing with N-related greenhouse gas (GHG) emissions, because such emissions and their impacts recognize no borders.

China is central to the issue. This is not only because China is the largest emitter of fossil-fuel CO_2 into the atmosphere (3) but because China has become a dominating force in the international N fertilizer market. In the past 2 decades (1990–2009), 61% of the world's increase in N fertilizer production and 52% of the increased N consumption occurred in China (4). In 2010, China produced 37.1 terrogram (Tg) of N (Tg N; agricultural consumption of 28.1 Tg N, industrial use of 4.7 Tg N, and export of 4.3 Tg N). This accounted for >30% of world's total and exceeded the combined N fertilizer use in North America (11.1 Tg N) and the European Union (10.9 Tg N) in 2009 (4). Furthermore, China's N fertilizer production and utilization have distinct characteristics. N fertilizer relies heavily on coal as the main source of energy in its production. Coal has a greater carbon footprint than other forms of energy, such as natural gas (Table S1). China's N fertilizer industry is fragmented, consisting of hundreds of small plants with a production capacity only a third to a quarter of typical facilities in developed countries (Table S2). These small enterprises often operate using outdated technologies with relatively low efficiency and high emissions. Perhaps the most striking difference between China and the developed economies is how fertilizer is used in the field. In contrast to the generally mechanized and integrated crop-soil-nutrient management practices widely adopted in developed countries, Chinese farmers hand-apply fertilizer to millions of small plots (Table 1), often resulting in gross overapplication (5). We believe that any global effort in N management must include strong participation by China, and quantifying the carbon footprint of China's N fertilizer chain requires the consideration of conditions specific to China.

Here, we quantitatively evaluate GHG emissions for China's N fertilizer chain through a life cycle analysis beginning from fossil fuel mining as the industry's energy source to postapplication of fertilizers in the field. To do these analyses, we used survey data of 230 fertilizer plants (Table S2) and synthesized literature data of 853 field measurements (Table S3), from which emission factors were derived. We then calculated annual GHG emissions from 1980 to 2010 using statistical data from the China Nitrogen Fertilizer Industry Association (Fig. S1) and estimated future emissions in 2020 and 2030 assuming a 1% annual increment (the same as in the past decade) in N fertilizer demand. Next, we explore emission reduction potential by identifying efficiency gaps between current technologies used in China and more advanced technologies available and by adjusting future N demand based on principles of rational N use that have been proven effective in developed countries and in China. We also discuss socioeconomic factors and propose policy changes that can help curb N-related GHG emissions and assist in moving toward low-carbon agriculture.

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Table 1. Survey results of farmers' practices regarding N fertilizer use in China

Items	Unit	Rice	Wheat	Maize	Fruits	Vegetables
No. of farmers interviewed		4,218	4,554	4,522	6,863	3,889
Synthetic N application	kg N ha^{-1}	209 ± 140*	197 ± 134*	231 ± 142*	550 ± 381*	383 ± 263*
	N applied as urea, %	51%	51%	50%	31%	31%
	N used as a single application, %	9%	26%	13%	16%	22%
	N used before planting, %	50%	60%	49%	—	11%
	N used by hand-broadcasting, %	96%	88%	36%	21%	8%
Manure N	kg N ha^{-1}	15 ± 48*	15 ± 55*	18 ± 52*	42 ± 99*	56 ± 145*
Crop yield	t ha^{-1}	7.2 ± 1.8*	4.9 ± 2.0*	7.4 ± 2.7*	36.7 ± 19.7*	36.0 ± 36.1*
Aboveground uptake	kg N ha^{-1}	122	123	162	128	83
Balance†	kg N ha^{-1}	102	89	87	464	356

This table comprises data taken from responses to a questionnaire survey conducted in 2009 (details are provided in *SI Text*).
*Number following a ± symbol is an SD.
†Balance = Synthetic N + Manure N − Aboveground Uptake.

Results and Discussion

Emission Factors Along the N Fertilizer Chain. For every ton of N produced and used on cropland in China, an average of 13.5 t of CO_2-equivalent (eq) (t CO_2-eq) is emitted (Fig. 1). The largest emission along the chain comes from ammonia synthesis (weighted average of 5.1 t CO_2-eq, 37.8% of 13.5 t). This is partly due to the energy-intensive nature of the chemical engineering process that requires high temperature and pressure and partly due to the low energy efficiency of coal as the main energy source. Coal-based facilities have an emission factor of >5 t CO_2-eq t NH_3-N^{-1} compared with <3 t CO_2-eq t NH_3-N^{-1} for natural gas-based plants (Table S4). For the same energy source, large-scale facilities emit slightly less GHGs per unit of N than medium- or small-scale facilities (Table S4). The next phase involves converting ammonia into various N fertilizer products; the processes have a weighted emission factor of 0.9 t CO_2-eq t N^{-1} but a wide range from 0.3 to 5.7 t CO_2-eq t N^{-1} (Table S5). Thereafter, transport and distribution of the N products have an emission factor averaging 0.1 t CO_2-eq t N^{-1}.

Coal supplies 86% of the energy consumed in the above processes. Methane emissions associated with coal mining have a global warming effect of 11.4 g CO_2-eq MJ^{-1} (10^6 J), compared with <2 g CO_2-eq MJ^{-1} with natural gas or oil (Table S1). We calculated a weighted emission factor of 2.2 t CO_2-eq t N^{-1} for the mining and transport of fossil fuel used in the N fertilizer industry (including 1.8 t CO_2-eq t N^{-1} from mining of the energy used for ammonia synthesis and 0.4 t CO_2-eq t N^{-1} for that used in N product manufacturing). This is 16% of the overall emissions of 13.5 t CO_2-eq t N^{-1}. Neglecting this component would lead to substantial underestimation of China's N fertilizer carbon footprint.

At the end of the chain are GHG emissions from agricultural fields receiving N fertilizers. Weighted for the quantities of N fertilizer used on upland crops and paddy rice systems, the emission factor is 5.2 t CO_2-eq t N^{-1}, including direct emission of N_2O (4.3 t CO_2-eq t N^{-1}) from nitrification and denitrification in soil and indirect emissions (0.9 t CO_2-eq t N^{-1}) calculated from N_2O emission via N deposition (associated with ammonia volatilization), nitrate leaching, and runoff. Our direct emissions are slightly greater, but indirect emissions are substantially less than Europe-based estimates (Table S3). In China, the dominant use of ammonium-based products, together with excessive N application, leads to substantial direct emissions of N_2O (5). As for indirect emissions, China's ammonia loss exceeds that in Europe because of surface spreading and overapplication of ammonia-based N products, but nitrate leaching loss is only a fraction of Europe's (Table S3) because of less nitrate-based products and lower rainfall in most regions of China (6, 7). Our calculations show that upland crop systems emit more GHGs than paddy rice fields, 5.9 t vs. 2.8 t CO_2-eq t N^{-1} (Table S3), which is comparable to Intergovernmental Panel on Climate Change (IPCC) values (6.2 vs. 2.9 t CO_2-eq t N^{-1}).

The overall emission factor we obtained (13.5 t CO_2-eq t N^{-1}) is greater than the estimate for the European N fertilizer chain (weighted average of 9.7 t CO_2-eq t N^{-1}; ref. 7), mainly because of higher emissions associated with coal mining as well as ammonia synthesis and fertilizer manufacture from a general lack of technological advancement in China (discussed elsewhere in this paper). Our results also differ from two previous studies involving China's N fertilizer-chain carbon footprint estimates. One estimated emissions at 9.6 t CO_2-eq t N^{-1} (8), and the other estimated emissions at 15–31 t CO_2-eq t N^{-1} (9). Their numbers were derived from limited data and did not include life cycle analyses.

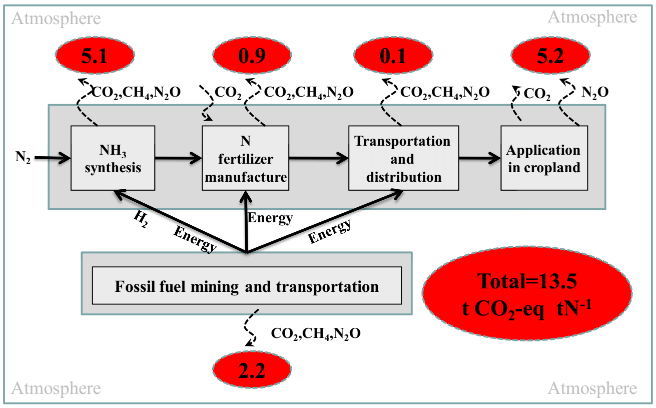

Fig. 1. Life cycle assessment of GHG emissions from manufacturing and field use of N fertilizer in China and weighted emission factors of main processes (system boundaries are described in the main text). Atmospheric nitrogen (N_2) is combined with hydrogen using energy from fossil fuels. The produced NH_3 is reacted with CO_2, nitric acid, hydrochloric acid, or phosphoric acid to produce different N fertilizer products. These fertilizers are transported by various means before being applied to croplands. The solid line represents the materials and N fertilizer flow. The broken line represents GHG exchanges between the fertilizer chain and the atmosphere.

Past, Present, and Future Emissions. Estimated N fertilizer-related GHG emissions in China totaled 131 Tg CO_2-eq in 1980 and increased steadily to 452 Tg CO_2-eq in 2010, with an average increase of 10.7 Tg CO_2-eq·y^{-1} (Fig. 2). This steep increase results directly from N fertilizer production and consumption trends (Fig. S1). In recent years, N-related GHG emissions account for about 7% of total emissions from China (6,100 Tg CO_2-eq in 2004, the most recent data available; ref. 10; Table S6). Assuming a 1% annual increment in agricultural demand for N while maintaining the same export (4.3 Tg N) and industry use (4.7 Tg N) as in 2010, China's N fertilizer demand for agriculture would amount to 33 Tg

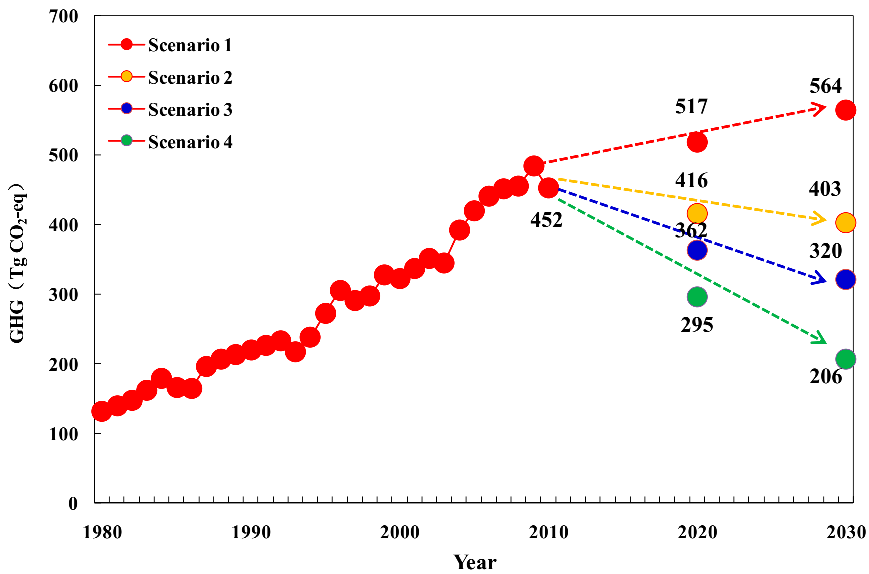

Fig. 2. GHG emissions associated with the N fertilizer chain in China. Emission amounts for 1980–2010 were calculated using emission factors (Fig. 1) derived from a 2005 survey and annual N production and consumption records. Emission estimates for 2020 and 2030 consider four scenarios: scenario 1, business-as-usual; scenario 2, improved manufacturing technologies; scenario 3, improved manufacturing technologies plus controlled N use; and scenario 4, improved manufacturing technologies with reduced N use on croplands.

N in 2020 and 36 Tg N in 2030. Associated GHG emissions would reach 517 Tg CO_2-eq and 564 Tg CO_2-eq, respectively. To put these numbers in perspective, total national GHG emissions from France and Germany in 2009 from all sources were 458 Tg N and 937 Tg CO_2-eq, respectively (11).

N fertilizer has played an indispensable role in doubling crop yields in China during the past 3 decades (12) and is estimated to have contributed to a net gain in soil organic carbon of 85 Tg per year (13). Nevertheless, our data show that N fertilizer-related GHG emissions are several times greater in magnitude than soil organic carbon gains. For China to reduce the gap between GHG emissions and soil carbon sequestration and to move toward low GHG emission agriculture, it is necessary to examine the entire N chain to identify potential emission reductions.

Potential Mitigation. Technological innovation can have a large impact on emission reduction, particularly at the beginning of the N fertilizer chain involving coal mining, ammonia synthesis, and N product manufacturing. For each of these sectors, we compare current technologies used in China with more advanced ones and also with the best technologies available worldwide to estimate emission reduction potential (Table 2).

i) Methane emissions from coal mining operations have a large global warming effect, and their recovery is only 15–23% in China (14, 15), compared with 35% with more advanced recovery technologies or 60% with the best system available (16). Adopting one or another of these would lower the emission factor from the current 0.24 t CO_2-eq t^{-1} coal to 0.20 or 0.14. The emission reduction benefit would extend beyond the N fertilizer industry because coal constitutes 70% of the total energy supplies in the entire country (12).

ii) Coal-fired electricity power plants in China have a heat conversion efficiency of 37–38% with the current subcritical engine units. Emerging technologies can increase the efficiency to 41–42% with supercritical units and to 46–48% with ultra-supercritical units (17). Adopting these new engine units would lower the carbon footprint for electricity from the current 1.12 kg CO_2-eq kilowatt-hour (kWh^{-1}) to 1.08 or 1.03 kg CO_2-eq kWh^{-1}. Again, the benefits would be applicable across the whole economy, and not just in the N fertilizer industry.

iii) The process of making NH_3 from atmospheric N_2 is energy-intensive; current technologies in China have an efficiency averaging 51.3 gigajoule (GJ) t NH_3-N^{-1}, compared with 43.7 GJ or 32.8 GJ t NH_3-N^{-1} with more advanced or the best technologies worldwide (18). Adopting the superior technologies would lower the emission factor from 5.1 to 3.2 or 2.4 t CO_2-eq t NH_3-N^{-1}.

iv) Urea is the main product, and its energy consumption could be lowered from 8.9 to 8.0 or 7.0 GJ t N^{-1} using better or the best available technologies. More dramatic impacts on emissions could potentially be achieved with ammonium nitrate (AN) production. China's AN production facilities mostly use 1960s' technologies, which consume 3.5 GJ t^{-1} N compared with 1.6 GJ t^{-1} N or even less with modern technologies (18). Moreover, AN manufacturing involves converting NH_3 into HNO_3, and the conversion process emits N_2O, currently at 8.0 kg N_2O t

Table 2. Energy use and GHG emissions from N fertilizer manufacture

Items		Unit	Currently in China	Advanced technology	Best technology
Coal mining CH_4 recovery		%	20*	35*	60*
Thermal efficiency at coal-fired power plants†		%	37–38	41–42	46–48
Energy use in NH_3 synthesis		GJ t NH_3-N^{-1}	51.3	43.7‡	32.8‡
Energy use in N product manufacturing	Urea	GJ t N^{-1}	8.9	8.0‡	7.0‡
	AN		3.5	1.6‡	0‡
N_2O emission in AN manufacture		kg N_2O t HNO_3^{-1}	8.0	1.9‡	0.5‡

*Coal bed methane recovery is reported to be 15–23% in China (14, 15); we take 20% as the average. Recoveries for advanced and best technologies are from a US Environmental Protection Agency publication (16).
†Data are from a study by Zhou (17).
‡Data are from a report by the International Fertilizer Association (18), with advanced technologies being the world average and the best technologies being those that operate at the highest energy efficiency.

HNO_3^{-1} in China, whereas an N_2O-abatement technology used elsewhere has lowered the emissions to 1.9 N_2O t HNO_3^{-1}, or even 0.5 kg N_2O t HNO_3^{-1} with the best technology (18). At present, AN is a minor product in China's N fertilizer portfolio (Fig. S1), but if the composition of N products is changed from ammonium-based to nitrate-based (see discussion below), adopting more efficient technologies at the manufacturing stage will be essential.

Combining all four components discussed above, we estimate the emission factor for the N fertilizer industry in China can be reduced from the current 8.3 t CO_2-eq t N^{-1} (2.2 for energy mining + 5.1 for ammonium synthesis + 0.9 for N product manufacture + 0.1 for fertilizer distribution; Fig. 1) to 5.8 or 4.7 t CO_2-eq t N^{-1} with more advanced or the best technologies (Table S7). In performing these analyses, we did not include "carbon capture and storage" technologies currently being tested in Europe and America (19) because these are still a long way from commercial use.

At the end of the N fertilizer chain, there is also considerable scope to reduce emissions resulting from application of fertilizers in the field. Adopting science-based fertilizer application practices is critically important (5, 20), as discussed in subsequent paragraphs. Here, we present some technological- and management-related options (Table 3). First, nitrate-based fertilizers are associated with less N_2O emission than urea or ammonium-based fertilizers (21) because most N_2O is generated from the nitrification process, at least in relatively low-rainfall regions, such as the North China Plain (22). This contrasts with many other regions in the world (and probably other regions in China), where denitrification appears to be the dominant process generating N_2O. Nitrate-based fertilizers also generate less ammonia loss than ammonium-based products (23). Therefore, adjusting the current N product makeup (with 97% being ammonium-based) may help reduce overall N_2O emissions in some regions. However, such a product shift must be preceded by upgrading the AN manufacturing technologies as mentioned previously; otherwise, N_2O emissions during HNO_3 production may exceed potential emission reductions downstream in the field. Second, urea is the main N product in China, and its surface-spreading is associated with considerable N loss via ammonia volatilization (5). Adopting subsurface application can greatly decrease ammonia volatilization, and therefore reduce indirect N_2O emissions (24). Still, possible tradeoffs exist. There may be greater N_2O emissions from nitrification and denitrification of subsurface-applied urea (25). The net effect on emissions will need to be evaluated for different regions, cropping systems, and management practices. Lastly, enhanced efficient fertilizers (including products with surface coatings or incorporating inhibitors of nitrification or urease activity) can improve N use efficiency and substantially reduce GHG emissions; a decrease of 77% in N_2O emissions from using nitrification inhibitors (22) or 60% in NH_3 losses from using urease inhibitors (24) has been reported. The downside of these products is the increased cost incurred (26), making them prohibitive for widespread adoption in grain crops unless incentives are introduced through subsidies or other measures as a means of enhancing environmental services.

Gross overapplication of N fertilizers in China has been well-documented, with a nationwide range of 30–60% above agronomically sound and environmentally sensible recommendations (5). The extent of N overuse is further illustrated by a large-scale survey we conducted recently with >13,000 grain producers and >10,000 fruit and vegetable farmers (Table 1). Excessive N use is widespread: Grain crops receive 220–270 kg N ha^{-1} but remove only 120–160 kg N ha^{-1}, fruits and vegetables receive 400–600 kg N ha^{-1} but remove only 83–130 kg N ha^{-1} (Table 1). The current situation is a result of numerous interacting economic, social, psychological, and policy factors, as discussed in a subsequent section of this paper.

At the national level, total N removal in aboveground crop parts amounted to 16.4 Tg in 2005 (27) and 17.2 Tg in 2010, and it will be 19.0 Tg by 2020 and 21.0 Tg by 2030 assuming a 1% annual increment in crop yield. Our recent work based on long-term intensively managed cropping systems in China shows that the optimum N rate for a crop approximates aboveground crop N removal (28). Applying this N balance concept would suggest that N fertilizer use nationally could be reduced by 42% from current use. Interestingly, the suggested 42% reduction is in line with direct experimental evidence that in two major grain-producing regions (the Yangtze Basin and the North China Plain), N rates can be reduced by 30–60% with no yield loss (5). Also, a rough balance between N fertilizer input and crop removal has been the case in general in developed countries (29).

To integrate the mitigation potentials discussed above and to evaluate their impacts on GHG emissions in coming decades, we performed scenario analyses (detailed data are provided in Table S7), and the results are summarized in Fig. 2. Scenario 1 is business-as-usual, maintaining current technologies and practices and assuming a 1% annual increment in domestic N fertilizer use (as in the past decade). GHG emissions would be 517 and 564 Tg CO_2-eq for 2020 and 2030, respectively. Scenario 2 assumes upgrading industrial technologies to the more advanced level by 2020 and to the best level by 2030 while maintaining the 1% annual increment in N demand. This would result in a net reduction of 102 Tg CO_2-eq by 2020 and 161 Tg CO_2-eq by 2030 compared with scenario 1. Scenario 3 includes the same technological advances as in scenario 2 but keeps N fertilizer at the 2010 level (i.e., no further increase; the rationale for this scenario is discussed later). This would further increase the net reduction (from the base scenario 1) to 155 Tg CO_2-eq for 2020 and to 243 Tg CO_2-eq for 2030. Scenario 4 integrates the technological advances in fertilizer manufacture with more rational N application to crops (achieved using the N balance approach discussed earlier), decreasing N fertilizer use by 21% in 2020 and 42% in 2030 (i.e., a two-step approach to reduce excessive N use). The net reduction (from the base scenario) would be 222 CO_2-eq for 2020 and 357 Tg CO_2-eq for 2030, respectively. There is considerable scope to replace some N fertilizer with livestock manure and probably through better integration of biological N fixation into cropping systems. Thus, further emission reductions are possible, but an in-depth analysis is beyond the scope of this paper.

Table 3. N losses following fertilizer application

Items	Field type	Unit	Currently in China	Advanced technology	Best technology
N_2O emission	Upland	kg N_2O-N kg N^{-1}	0.0105	0.01*	0.007†
	Paddy		0.0041	0.003*	0.003*
NH_3 losses	Upland	kg NH_3-N kg N^{-1}	0.129	0.1*	0.02‡
	Paddy		0.179	0.1*	0.1*
NO_3^- losses	Upland	kg NO_3-N kg N^{-1}	0.098	—	0.04§
	Paddy		0.014	—	—

*Data are from a publication by the IPCC (37) (i.e., IPCC default values, which were mostly derived based on developed economies).
†Data are from a study by Bouwman et al. (21), assuming replacement of urea with $Ca(NH_4)(NO_3)_3$.
‡Data are from a report by the International Fertilizer Association (23), assuming replacing urea with $Ca(NH_4)(NO_3)_3$.
§Data are from a study by Li et al. (39), based on experimental results using nitrate inhibitors.

Overall, the magnitude of potential reductions associated with the various scenarios, ranging from 102 to 357 Tg CO_2-eq, represents a 1.7–5.9% reduction in China's total GHG emissions from all sources (2005 value). This is significant nationally and globally because the feasible emission reductions from improvements in the N fertilizer chain in China are similar in magnitude to the total national reduction goals for 2020, from all sources, sought by several countries [e.g., Germany (365 Tg), France (158 Tg), and the United Kingdom (235 Tg)] (30).

General Discussion

Our analysis, using a life cycle assessment approach, demonstrates that it is essential to include the manufacturing component of the N fertilizer chain (even extending to methane emissions from the mining of coal as an energy source for N manufacture) because these parts of the chain constitute 61% of total emissions (Fig. 1) and provide considerable scope for substantial GHG reductions (scenario 2). China's N fertilizer industry consists of ∼500 companies, as opposed to >200 million individual farmers at the "utilization" end of the chain; thus, it should be easier in the short to medium term to achieve changes in the manufacturing processes through technological innovation and government action. Large capital investment is required for this transformation. One possible solution is for the Chinese government to reallocate the large subsidies, roughly US $7.46 billion during 2008–2009 alone (31), provided to the fertilizer industry through tax breaks and energy subsidies, for technological upgrading of fertilizer plants. Another option is through international intervention via mechanisms, such as carbon trade/credits to accelerate technological advancement. More detailed discussion of the issue and a cost–benefit analysis are beyond the scope of this paper, but we hope this analysis stimulates international interests in upgrading the N fertilizer production chain in China.

China has to grow food to feed >20% of the world's population with only 9% of the world's arable land. Consequently, food security remains the top priority above other concerns unlike the case in developed economies, where national-scale food security is not a major concern (32). This is the basis for scenario 3, where we consider maintaining N fertilizer use at the 2010 level without further increases. This means putting an end to the 50-y trend of increased N production and use. This is not to be taken lightly, because to many, decision makers and farmers alike, continuous growth in agricultural output is thought to depend on increasing fertilizer input. Although still undesirable environmentally, this scenario is probably more likely than scenarios with fertilizer use reductions, given China's political and societal modes.

Clearly, minimizing N fertilizer overuse at the end of the chain is vital. This would not only enhance N fertilizer efficiency and lower emissions in fertilized fields but, more importantly, decrease the total amount of N fertilizer demand. The latter means emission reductions involving the entire N fertilizer chain. Various factors contribute to the excessive N use in China. First, fertilizers have been kept at artificially low prices through heavy government subsidies (31), which obscure the financial burden resulting from excessive N use. Second, there is the absence of an effective and functional extension system that can reliably and systematically deliver science-based recommendations and techniques to hundreds of millions of farmers, although such recommendations have been developed for all major crops and cropping systems in China (33). Third, the land is farmed in small parcels, averaging <0.1 ha per household, which hinders the development and adoption of technologies for mechanized fertilizer application with better control and precision. Fourth, rapid economic development in China has led to the phenomenon of "part-time farmers" because many rural people, especially better educated younger people, are moving into nonfarm work, and this is often more important for household incomes than farming. Consequently, classic models of agricultural extension and assumptions of increasing technical understanding by farmers may no longer be applicable. Improving delivery of technical information at the farm level to enhance N fertilizer use efficiency has value but has been demonstrated to be slow in altering farmer behavior. We propose that alteration of policies related to fertilizer production will be more effective in delivering the necessary changes. Current N fertilizer-related policies were devised decades ago, with the aim of increasing N application for enhanced crop production (*SI Text*). These policies now need to be revised to address both food security and sustainability issues. The huge subsidies to maintain low fertilizer cost for farmers should be replaced with programs that promote environmental services without threatening national food security. For example, incentive programs are needed to improve the management and enhance the utilization of large amounts of livestock manure generated in the nation, which, in turn, would allow substantial reduction of chemical fertilizers (27). Also, payments can be made to cover the additional cost of nitrate-based fertilizer and enhanced efficient fertilizers in situations in which there is clear evidence that these will increase N use efficiency and decrease the amount of N needed. Furthermore, financial support to promote the development of a contractor sector for fertilizer application can be beneficial. Such contractors can (*i*) purchase machinery for subsurface urea application, decreasing ammonia losses; (*ii*) apply N at the "right time," overcoming the labor shortage problem; and (*iii*) comprise a professional group to receive technical information on N fertilizer management.

Conclusions

N fertilizer has been and will continue to be indispensable for China's quest to produce sufficient food to meet its growing demands. However, decades of excessive N use have contributed to a variety of environmental problems, including large GHG emissions and serious water pollution. Our life cycle analysis shows the significance of the carbon footprint associated with the N fertilizer chain in China. GHG emissions tripled from 1980 to 2010, with the amount growing from 131 to 452 Tg $CO_2\text{-eq}\cdot y^{-1}$, and, if unabated, to 564 Tg $CO_2\text{-eq}\cdot y^{-1}$ by 2030. China needs a combination of reforms in the fertilizer industry and changes in management practices and technologies at the farm level to minimize excessive N use in the field. Our scenario analysis indicates it is feasible to reduce GHG emissions by 20–43% from a "business as usual" scenario by 2020 if an appropriate range of mitigation measures are introduced covering both N fertilizer manufacture and its agricultural use. The corresponding reduction by 2030 is 29–63%. Such reductions are in the range of 1.7–5.9% of current national total emissions from all sources. A reduction of this magnitude makes a highly significant contribution to national goals of moving toward a low-carbon economy and is highly significant globally. Minimizing N fertilizer overuse will also deliver "multiple wins" [e.g., improved water quality (with benefits for fish production), enhanced air quality (with associated benefits for human health), less acidification of the soil, improved income for farmers, greater spending power in the rural economy].

Materials and Methods

Life Cycle Assessment Approach for N Fertilizer Chain. We used a life cycle assessment approach to estimate GHG emissions due to the main components of the N fertilizer chain in China, primarily using Chinese-specific parameters rather than IPCC tier 1 default values. According to the International Organization for Standardization's International Standard ISO 14042 (34), the life cycle of N fertilizer should be conducted from "cradle to grave." Therefore, we include GHG emissions associated with mining of fossil fuel used for fertilizer production, transport of fossil fuel, fertilizer synthesis, fertilizer transport and distribution, and gaseous emissions (direct and indirect) when fertilizers are applied to farmland (Fig. 1).

GHG Emission from Fossil Fuel Mining. Two published studies have estimated the GHG emission factors (CO_2, CH_4, and N_2O) in Chinese energy production systems (coal, natural gas, oil, and electricity) using a life cycle assessment approach (14, 35). We used these China-specific emission factors in our study (details are provided in Table S1).

GHG Emission from Ammonia Synthesis. Ammonia is the primary material from which various N fertilizer products are produced. Ammonia synthesis is a major contributor to GHG emissions because of the large energy requirement for its manufacture. The Chinese Nitrogen Fertilizer Industry Association (CNFIA) surveyed 230 companies (Table S2), which account for 40% of the total N fertilizer industry in the nation, including all the large- and medium-scale plants. The survey collected information on the total energy consumption between 2002 and 2005. We have adopted the raw material consumption rate of the ammonia industry determined by this survey and classified the industry into eight categories to estimate different GHG emission factors associated with ammonia synthesis (Table S4).

GHG Emission from N Fertilizer Manufacture. As is the case with NH_3 synthesis, a range of different processes are used in the manufacture of specific fertilizer products. We included five N fertilizer products in this study: urea; AN; ammonium bicarbonate (ABC); ammonium chloride; and compound fertilizers containing N, phosphorus, and potassium (NPKs). We used the specific energy consumption rate of each product determined by the CNFIA survey and by Fan et al. (36) and estimated a GHG emission factor for each (Table S5). The CO_2 fixed during the production of urea and ABC is emitted later into the atmosphere when the fertilizers are applied in the field; thus, it was not included in the calculations.

GHG Emission from Transporting Energy and N Fertilizer Products. We obtained the average transportation distances by train and truck in China for coal, crude oil, and N fertilizer from the National Bureau of Statistics of China (12). We adopted the IPCC (37) default emission factors for N_2O, CH_4, and CO_2 for energy combustion by internal-combustion engines for vehicle transportation (Table S8). Combining these values, we estimate GHG emission factors for energy and fertilizer transportation (details are provided in *SI Text*).

GHG Emission from Postapplication Field. The GHG emissions caused by N fertilizer applied to croplands are mainly in the form of N_2O, including direct and indirect emissions. We classified Chinese agricultural land into two groups: upland fields and paddy fields. We compiled all published field measurements in China (a total of 853) and summarized the results using a meta-analysis method to derive direct and indirect N_2O emission factors. Direct emission factors for upland fields and paddy fields were obtained from a study by Gao et al. (38), which includes 456 N_2O emission measurements in China (195 paddy fields and 261 upland fields). Indirect emissions include N_2O resulting from N deposition (associated with NH_3 volatilization) and NO_3^- leaching. We summarized 397 published field measurements (138 paddy fields and 259 upland fields) from 47 literature sources. We used IPCC (37) values for the proportion of those losses emitted as N_2O (Table S8). Then, we calculated the GHG emission factors for paddy fields and upland fields, respectively (Table S3).

Total GHG Emissions from N Fertilizer Production and Utilization. We calculated annual total GHG emissions from N fertilizer production and consumption in China from 1980 to 2010. The emission factors for the various sectors (energy mining and transport, NH_3 synthesis, fertilizer manufacture, N products distribution, and N application) were multiplied by the respective quantities of the materials to derive the amounts of sector-specific emissions, which were then summed for each year (details are provided in *SI Text*).

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