Supplementary File 1: Supplementary methods to this study.

Food and protein consumption

Historical data on China's population, grain and animal production were obtained from China's national statistics between 1961 and 2018, including the *Compilation of China Agricultural Statistics* and *Statistical Bulletin on National Economic and Social Development*. Plant-based food and animal-based food (meat, eggs and milk) consumption was calculated based on the net plant food supply (production + import-export), assuming approximately 20% of total food supply as food waste[1][2]. The mean daily protein intake per capita was calculated as the sum of protein from all plant and animal food products, excluding those used for animal feeds (50% of plant products). Annual N intake per capita (kg N capita^{-1} yr^{-1}) was estimated by multiplying daily protein intake (g capita^{-1} day^{-1}) with the protein N content (16%) and 365 days in a year:

$$\text{Annual N intake} = \text{Daily protein consumption} \times 0.16 \times 365 \times 0.001 \quad (1)$$

The ratio of animal protein to total (plant+animal) protein was calculated as:

$$\text{Animal protein ratio} = \text{Animal protein intake/Total (plant+animal) protein intake} \quad (2)$$

N saving potentials

We analyzed N saving potentials for China's crop production based on three approaches. First, we focused on the replacement of chemical N fertilizer with an increasing proportion of recycled manure, an approach based on setting an equal nutrient value for N from chemical fertilizer and manure in the long-term [3],[4]. We analyzed N saving potentials from technical innovations using the so-called 4R strategy [5],[6], i.e., the use of improved fertilizer products (Right N products), that are applied at the right amount, right time, and right place. To realize the 4R strategy, we used balanced fertilization (Right amount) for saving N as the second step. Then we adopted integrated approaches (the other 3Rs) for further optimizing N inputs as the third step. The basis for the calculations is as follows:

(1) *N fertilizer replacement at 80% manure recycling*. Based on Bai et al [7] and Kang et al [8], only 20% of the N intake by livestock is excreted onto grazed land. This implies that 80% of manure can be recycled. The amount of available recycled manure N for croplands was estimated at 9.8 Tg N yr^{-1} assuming a recycling efficiency of 80%, while current manure N input was estimated at 5.6 Tg N yr^{-1} in 2018 (Supplementary Table S3). Thus 80% recycling of N in manure would lead to an additional saving of 4.2 Tg N yr^{-1} (plus the already recycled 5.6 Tg N yr^{-1}), which is approximately equal to 34% of fertilizer N in 2018.

(2) *Balanced N fertilization*. This approach implies that the N requirement of crops is balanced by all N inputs, including the input of non-N fertilizer sources, i.e. manure, deposition and irrigation, thus allowing a lower N fertilizer input. Considering a similar NUE for all N sources, China's average NUE was 45% in 2018. Xia, et al [9] suggest that an overall decrease of N fertilizer by 1/3 is possible, implying a total NUE of 63% is achievable.

(3) *Integrated approaches*. These refer to integrated soil–crop system management, including the 4R

technologies (right rate, right type, right place, and right time of fertilizer application), optimised irrigation practices, improved soil and crop management based on 80% manure recycling and balanced N fertilization. This can result in an overall increase in NUE to 73%, which is slightly higher than the expected NUE in Europe in 2050.

Cost savings

The proposed changes in N management will lead to direct and indirect economic benefits. Direct benefits include a reduction in N fertilizer costs. Based on the cost of urea of about 300–500 Euro per ton and an N content of 46%, we calculated N fertilizer costs to be 0.6–1.0 Euro per kg N with an uncertainty of 50% to account for the price differences among different types of fertilizers. The indirect benefits from reduced heath costs and environmental improvement were based on the willingness to pay (WTP) in the EU27 [10] corrected for the ratio of gross domestic product (GDP) per capita in China to that in EU27. The WTP for China was derived from the corrected values from the EU due to various N losses to air and water given in Supplementary Table S5.

Uncertainties

The estimated country totals for N inputs, N uptake and N losses to air and water are all prone to uncertainties. In line with Kros et al. [11], who performed an uncertainty assessment of N inputs and N outputs for the EU27, we used three levels of uncertainties for the coefficient of variation (CV) including a low (0.10), moderate (0.25) and high (0.50) uncertainty. We used a Monte Carlo analysis to assign the ranges in N emissions, leaching and runoff, i.e. 20% for NH_3 emissions, and 30% for N_2O and NO_x emissions and 30% for N leaching plus runoff. These uncertainties are based on the most conservative assumptions for the EU27, considering a higher uncertainty in input data for China as compared to the EU27. The results showed that N balances in maize, wheat and rice systems fit a normal distribution (Supplementary Fig. S6). These uncertainties are expected to be systematic rather than random, and therefore do not affect conclusions based on temporal comparisons.

References

[1] Erisman J W, Sutton M A, Galloway J, Klimont Z, Winiwarter W, et al. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience.* 1:636-639. https://doi.org/10.1038/ngeo325

[2] Foyer C H, Lam H M, Nguyen H T, Siddique K H M, Varshney R K , et al. 2016. Neglecting legumes has compromised human health and sustainable food production. *Nature Plants.* 2: 16112 https://doi.org/10.1038/NPLANTS.2016.112

[3] Duan Y H, Xu M G, Wang B R, Yang X Y, Huang S M, et al. 2011. Long-term evaluation of manure application on maize yield and nitrogen use efficiency in China. *Soil Science Society of America Journal*.75:1562-1573.

[4] Li H, Feng W T, He X H, Zhu P, Gao H J, et al. 2017. Chemical fertilizers could be completely replaced by manure to maintain high maize yield and soil organic carbon (SOC) when SOC reaches a threshold in the Northeast China Plain. *Journal of Integrative Agriculture* 16: 937-946. https://doi.org/10.1016/S2095-3119(16)61559-9

[5] Bruulsema T. 2009 In *Proceedings of the North Central Extension-Industry Soil Fertility Conference*. Volume 25. Des Moines, IA.

[6] Liu X J, Cui Z L, Hao T X, Yuan L X, Zhang Y, et al. 2022. A new approach to holistic nitrogen management in China. *Frontiers of Agricultural Science and Engineering*, 9:490-510.

[7] Bai Z H, Ma L,Jin S Q, Ma W Q, Velthof G L, et al.2016. Nitrogen, phosphorus, and potassium flows through the manure management chain in China. *Environmental Science & Technology.* 50:13409-13418 https://doi.org/10.1021/acs.est.6b03348

[8] Kang Y N, Liu M X, Song Y, Huang X, Yao H, et al. 2016. High-resolution ammonia emissions inventories in China from 1980 to 2012. *Atmospheric Chemistry and Physics.* 16: 2043-2058 https://doi.org/10.5194/acp-16-2043-2016

[9] Xia L L, Lam S K, Chen D L, Wang J Y, Tang Q, et al. 2017. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Global Change Biology.* 23: 1917-1925 https://doi.org/10.1111/gcb.13455

[10] Van Grinsven H J M, Holland M, Jacobsen B H, Klimont Z, Sutton M A, et al. 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. *Environmental Science and Technology.* 47: 3571-3579 https://doi.org/10.1021/es303804g

[11] Kros J, Heuvelink G B M, Reinds G J, Lesschen J P, Ioannidi V, et al. 2012. Uncertainties in model predictions of nitrogen fluxes from agro-ecosystems in Europe. *Biogeosciences* 9; 4573-4588 https://doi.org/10.5194/bg-9-4573-2012