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Managing nitrogen for sustainable development

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Improvements in nitrogen use efficiency in crop production are critical for addressing the triple challenges of food security, environmental degradation and climate change. Such improvements are conditional not only on technological innovation, but also on socio-economic factors that are at present poorly understood. Here we examine historical patterns of agricultural nitrogen-use efficiency and find a broad range of national approaches to agricultural development and related pollution. We analyse examples of nitrogen use and propose targets, by geographic region and crop type, to meet the 2050 global food demand projected by the Food and Agriculture Organization while also meeting the Sustainable Development Goals pertaining to agriculture recently adopted by the United Nations General Assembly. Furthermore, we discuss socio-economic policies and technological innovations that may help achieve them.

More than half the world's people are nourished by crops grown with synthetic nitrogen (N) fertilizers, which were made possible in the early twentieth century by the invention of the Haber–Bosch process, which reduces atmospheric nitrogen gas (N_2) to reactive forms of N (ref. 1). A reliable supply of N and other nutrients essential for plant growth has allowed farmers to increase crop production per unit land greatly over the past century, thus promoting economic development, allowing larger populations, and sparing forests that would probably otherwise have been converted to agriculture to meet food demand[2]. Despite this progress, nearly one billion people remain undernourished[3]. In addition, the global population will increase by two to three billion by 2050, implying that demands for N fertilizers and agricultural land are likely to grow substantially[2,4]. Although there are many causes of undernourishment and poverty, careful N management will be needed to nourish a growing population while minimizing adverse environmental and health impacts.

Unfortunately, unintended adverse environmental and human health impacts result from the escape of reactive N from agricultural soils, including groundwater contamination, eutrophication of freshwater and estuarine ecosystems, tropospheric pollution related to emissions of nitrogen oxides and ammonia gas, and accumulation of nitrous oxide, a potent greenhouse gas that depletes stratospheric ozone[5–9] (Fig. 1). Some of these environmental consequences, such as climate change and tropospheric ozone pollution, can also negatively affect crop yields[10,11] and human health[12]. Hence, too little N means lower crop productivity, poor human nutrition and soil degradation[13], but too much N leads to environmental pollution and its concomitant threats to agricultural productivity, food security, ecosystem health, human health and economic prosperity.

Improving nitrogen-use efficiency (NUE)—that is, the fraction of N input harvested as product—is one of the most effective means of increasing crop productivity while decreasing environmental degradation[14,15]. Indeed, NUE has been proposed as an indicator for assessing progress in achieving the Sustainable Development Goals recently accepted by 193 countries of the United Nations General Assembly[16]. Fortunately, we have a large and growing knowledge base and technological capacity for managing N in agriculture[17], and awareness is growing among both agricultural and environmental stakeholder groups that N use is both essential and problematic[15]. This growing awareness, combined with ongoing advances in agricultural technology, is creating a possible turning point at which knowledge-based N management could advance substantially throughout the world. However, improving NUE requires more than technical knowledge. The cultural, social and economic incentives for and impediments to farmer adoption of NUE technologies and best management practices need to be better understood[15].

Here we analyse historical patterns (1961–2011) of agricultural N use in 113 countries to demonstrate a broad range of pathways of socio-economic development and related N pollution. Our analysis suggests that many countries show a pattern similar to an environmental Kuznets curve (EKC), in which N pollution first increases and then decreases with economic growth[18–21]. So far, most EKC analyses have focused on pollution from industrial and transportation sectors[19,22,23]; the present study is one of a few that consider agricultural N pollution in the EKC context[24,25], and apply it globally. However, patterns of N pollution are neither automatic nor inevitable. Socio-economic circumstances and policies vary widely among countries, affecting factors such as fertilizer to crop price ratios and crop mixes, which, as our analysis shows, influence the turning points of the EKC. Although technological and socio-economic opportunities for NUE improvement vary regionally, our analysis shows that average global NUE in crop production needs to improve from ~0.4 to ~0.7 to meet the dual goals of food security and environmental stewardship in 2050.

Patterns of nitrogen pollution

As a useful indicator of potential losses of N to the environment from agricultural soils[26,27], N surplus (N_{sur}; in units of kg N ha^{-1} yr^{-1}) is defined as the sum of N inputs (fertilizer, manure, biologically fixed N, and N deposition) minus N outputs[28,29] (the N removed within the harvested crop products, N_{yield}; Fig. 1). Some of the N_{sur} recycles within the soil, but most N_{sur} is lost to the environment over the long term, because the difference between annual inputs and outputs is usually large relative

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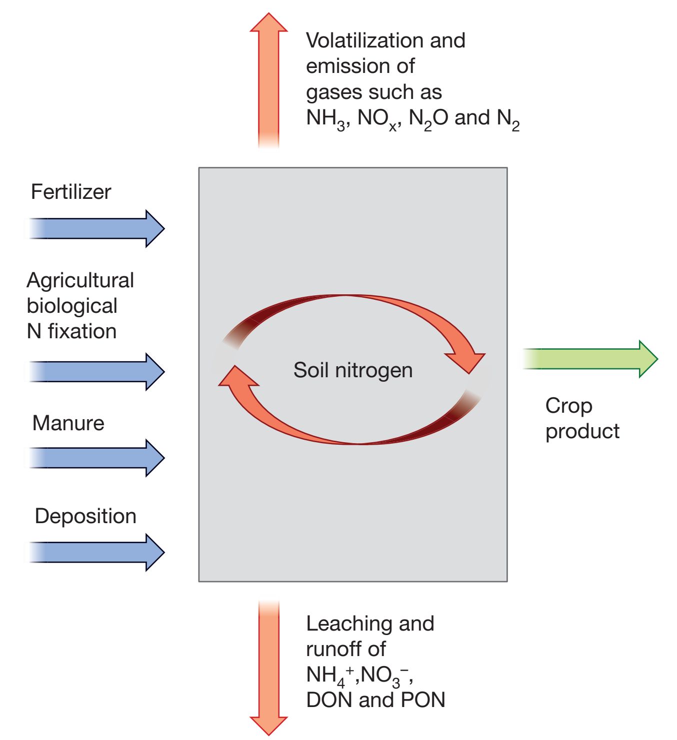

Figure 1 | An illustration of the N budget in crop production and resulting N species released to the environment. Inputs to agriculture are shown as blue arrows and harvest output as a green arrow. NUE is defined as the ratio of outputs (green) to inputs (blue) (i.e. NUE = N_{yield}/N_{input}). The difference between inputs and outputs is defined as N_{sur}, which is shown here as orange arrows for N losses to the environment and as N recycling within the soil (grey box) (that is, $N_{sur} = N_{input} - N_{yield}$). Abbreviations: ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), dinitrogen gas (N_2), ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic nitrogen (DON) and particulate organic nitrogen (PON).

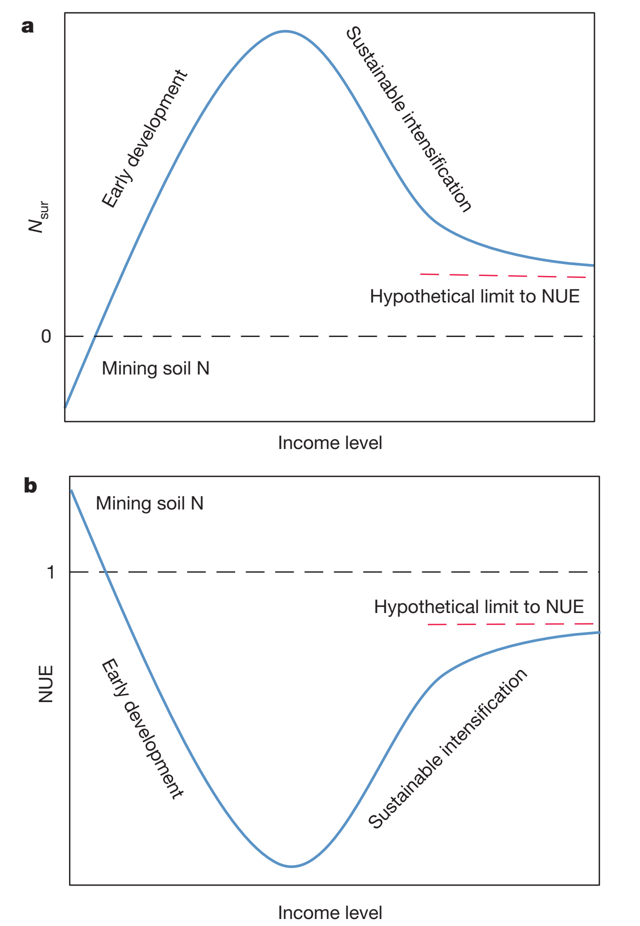

Figure 2 | An idealized EKC for N_{sur} and the related curve for NUE. **a**, The EKC for N_{sur}. **b**, The curve for NUE, which is related to the EKC for N_{sur}. The theoretical limit for NUE (assuming no soil mining of nutrients) is unknown, but no biological system is 100% efficient, so the hypothetical NUE limit is shown as close to but less than unity.

to changes in soil N stocks. The related term of NUE, also called the output–input ratio of N, is mathematically defined as the dimensionless ratio of the sum of all N removed in harvest crop products (outputs or N_{yield}) divided by the sum of all N inputs to a cropland[30,31] (Fig. 1). The N_{sur}, NUE and N_{yield} terms can serve as environmental pollution, agricultural efficiency, and food security targets[32,33], respectively, which are inherently interconnected through their mathematical definitions[33] (that is, $N_{sur} = N_{yield}\left(\frac{1}{NUE} - 1\right)$, see Supplementary Information section 1 for more information) and their real-world consequences (Fig. 1).

Variable turning points on the EKC

As an indicator of the extent of environmental degradation, N_{sur} aggregated to a national average for all crops is closely related to income growth, mainly in two contrasting pathways as follows. On the one hand, increasing income enables demand for more food consumption[33], which can increase both the land area devoted to agriculture and the intensity of agricultural production and consequently results in more N lost to the environment. On the other hand, increasing income is often accompanied by a societal demand for improved environmental quality, such as clean water and clean air, and is also accompanied by access to advanced technology[18,19]. Consequently, governments may impose regulatory policies or offer subsidies and incentives targeted at reducing local or regional N pollution, and farmers may adopt more efficient technologies.

Therefore, we hypothesize that N_{sur} follows a pattern similar to the EKC: N_{sur} increases with income growth and the quest for food security at early stages of national agricultural development (first phase), but then decreases with further income growth during a more affluent stage (second phase), eventually approaching an asymptote determined by the theoretical limit of the NUE of the crop system (third phase, Fig. 2).

Sustainable intensification of agriculture has been advanced as the key to achieving the second phase of the EKC, including use of cultivars best adapted to the local soil and climate conditions, improved water management, balancing N application with other nutrient amendments, precision timing and placement of fertilizer and manure applications to meet crop demands, the use of enhanced-efficiency fertilizers, and support tools to calculate proper dosing[14,17,34]. While N_{sur} is the EKC environmental degradation indicator, the mathematical relationship between N_{sur} and NUE results in nearly mirror images in Fig. 2 (although see Supplementary Information section 1 for a discussion of situations in which N_{sur} and NUE can both increase simultaneously).

Of the three phases of the N_{sur} trend, it is the second phase of sustainable intensification with increasing affluence that is of greatest contemporary interest. The first phase of agricultural expansion is well documented[30,31], and the third phase cannot yet be evaluated. So far, no country has yet approached the third phase, nor do we know how close to 100% efficiency the use of N inputs could become. For the first phase, as incomes rise, virtually all countries initially increase fertilizer use, N_{yield}, and N_{sur} while NUE decreases[30,31]. To test the existence of the second phase, we examine whether the relationship between gross domestic product (GDP) per capita and N_{sur} breaks away from the linearly (or exponentially) increasing trend and follows more of a bell-shaped pattern over the long term.

We tested the existence of a sustainable intensification phase (or an EKC pattern) with a five-decade record (1961–2011) of N_{sur} and GDP per capita[28,35–40] with a fixed effects model[41–43] across 113 countries for which sufficient data were available and a regression model for each individual country[18,44–46] (see sections 1 and 2 in the

Supplementary Information). The fixed effects model shows a significant quadratic relationship between GDP per capita and N_{sur} ($P < 0.001$, Supplementary Table 9). Regressions between GDP per capita and N_{sur} for each individual country fall into five response types (examples of each group are shown in Fig. 3). Of the 113 countries, 56 countries (group 1) show bell-shaped relationships between N_{sur} and GDP per capita, indicating that N_{sur} increased and then levelled off or decreased as economic development proceeded, as expected for an EKC (two examples are illustrated in Fig. 3a). Those 56 countries account for about 87% of N fertilizer consumption and about 70% of harvested area of all 113 countries. These data provide support for an EKC pattern for N pollution from agriculture, although as we show below, the potential causes of EKC shapes and turning points are complex. Furthermore, for 28 of the 56 countries, by 2011 the rate of increase in N_{sur} had only slowed or levelled off and had not yet actually decreased, indicating likely but still uncertain conformance with an EKC (Supplementary Tables 5 and 6).

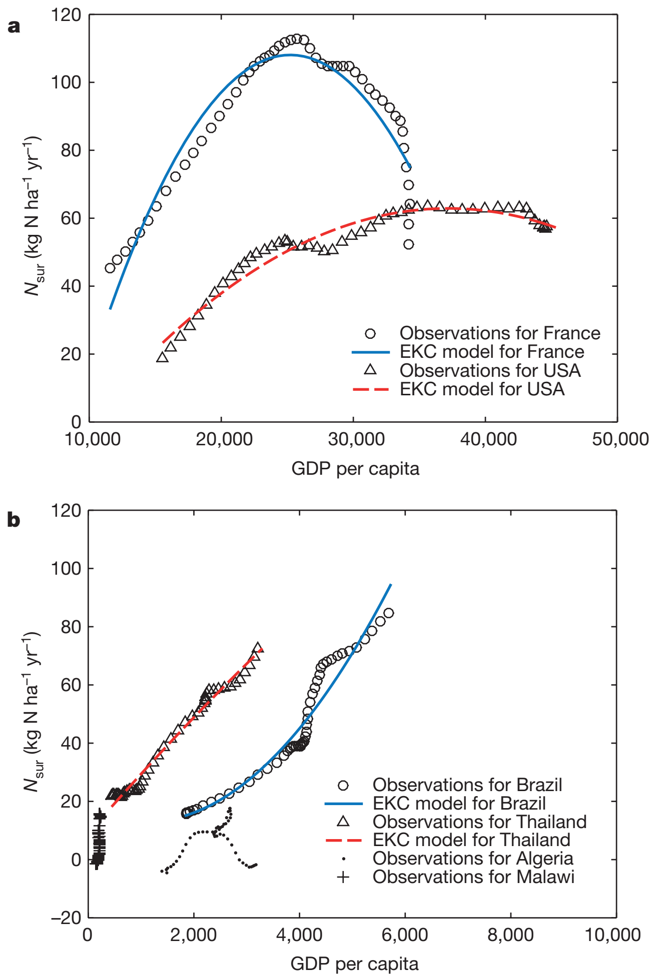

Figure 3 | Examples of historical trends of the relationship between GDP per capita and N_{sur}. The observations are the record of annual N_{sur} smoothed using a ten-year window for each country; the model results are the outcome of the regression using the following model: $Y = a + bX + cX^2$, where the dependent variable Y is the country's N_{sur} and the independent variable X is the country's GDP per capita. We categorized the 113 countries into five groups, based on the significance (that is, P value) and sign of the regression coefficients b and c (see Supplementary Information sections 2.1 and 3.1). **a**, France and USA are examples of group 1, which have significantly negative c ($P_c < 0.05$ and $c < 0$), thus indicating that N_{sur} has started to level off or has declined; **b**, Brazil, Thailand, Malawi and Algeria are examples of groups 2–5, which increase nonlinearly, increase linearly, have no significant correlation ($P_b > 0.05$ and $P_c > 0.05$), or have a negative surplus in 2007–2011, respectively (see Supplementary Tables 5 and 6). The results for all countries can be found in the figures in the Supplementary Information.

Countries with a linear or accelerating increase in N_{sur} (group 3 and most countries in group 2) as GDP per capita grew have not yet approached an EKC turning point (for example, Fig. 3b), but could still follow an EKC in the future as their N input growth slows and NUE increases. Most countries showing an insignificant ($P > 0.05$) relationship between N_{sur} and GDP per capita (group 4) or with a negative N_{sur} (group 5) have had such little income growth and use so little N that the EKC concept cannot be evaluated yet owing to limited change in the country's GDP per capita (for example, Fig. 3b).

Classic empirical studies on EKC, such as Grossman and Krueger (ref. 19), have been criticized because of concerns regarding statistical analyses of time series data that may be non-stationary[47–49]. Therefore, we examined the stationarity of our data (Supplementary Table 7) and used the Autoregressive Distributed Lag modelling approach (ARDL)[50], which is the most frequently used method for the co-integration test in EKC empirical studies published in the last decade[43], to test co-integration on a subset of the data. The ARDL regression models showed the same long-term relationships between N_{sur} and GDP per capita as presented above for all tested countries (Supplementary Table 8). The application of the ARDL method in EKC studies has also been criticized recently for including the quadratic term in the co-integration test, and some new methods have been proposed[51,52]. Further evaluation is needed on the limitations and performance of the ARDL and newly proposed methods for EKC analyses.

Another common criticism of the EKC concept is that the turning point for transitioning to declining environmental degradation is highly variable among pollutants and among countries[18,53,54]. Consistent with those observations, no specific value of GDP per capita was a good predictor of turning points for N_{sur} on the EKC among countries in the present study. For example, N_{sur} in Germany and France started to decline when GDP per capita reached about US$25,000 in the 1980s, while N_{sur} in the USA levelled off and started to decline more recently when GDP per capita reached about US$40,000. Our analysis also shows that countries have widely differing values of NUE and N_{sur} even when yields are similar. Some of this variation is probably due to underlying biophysical conditions, such as rainfall variability and soil quality, which influence crop choices, yield responses, and NUE. However, cultural, social, technological, economic and policy factors also probably affect the turning points on the EKC trajectory of each country.

The turning point in European Union (EU) countries appears to have been reached at least in part owing to policies[55]. Beginning in the late 1980s and through the early 2000s, increases in NUE and decreases in N_{sur} in several EU countries coincided with changes in the EU Common Agricultural Policy, which reduced crop subsidies, and adoption of the EU Nitrates Directive, which limited manure application rates on cropland[56,57]. Relying mostly on volunteer approaches in the USA, the levelling off and modest decrease in N_{sur} since the 1990s is largely the result of increasing crop yields while holding N inputs steady (Fig. 4a), which has resulted from improved crop varieties, increased irrigation and other technological improvements[57,58]. A few state regulatory programmes have required nutrient management plans, placed limitations on fertilizer application dates and amounts, and required soil and plant testing, with varying degrees of success[58–60]. Concerns about water and air quality, estuarine hypoxic zones, stratospheric ozone depletion, and climate change have also stimulated many outreach efforts by governments, fertilizer industry groups, retailers, and environmental organizations to provide farmers with information, training and innovative financial incentives to improve NUE voluntarily[15,59,61,62].

Fertilizer to crop price ratios

Policy can affect NUE not only through regulation and outreach, but also by affecting prices at the farm gate. The ratio of fertilizer to crop prices, R_{fc}, has been widely used in combination with data on yield responses to fertilizer application to advise farmers on fertilizer application rates that yield optimal economic returns[63–65]. In addition to influencing fertilizer application rates, R_{fc} also affects farmer decisions regarding their

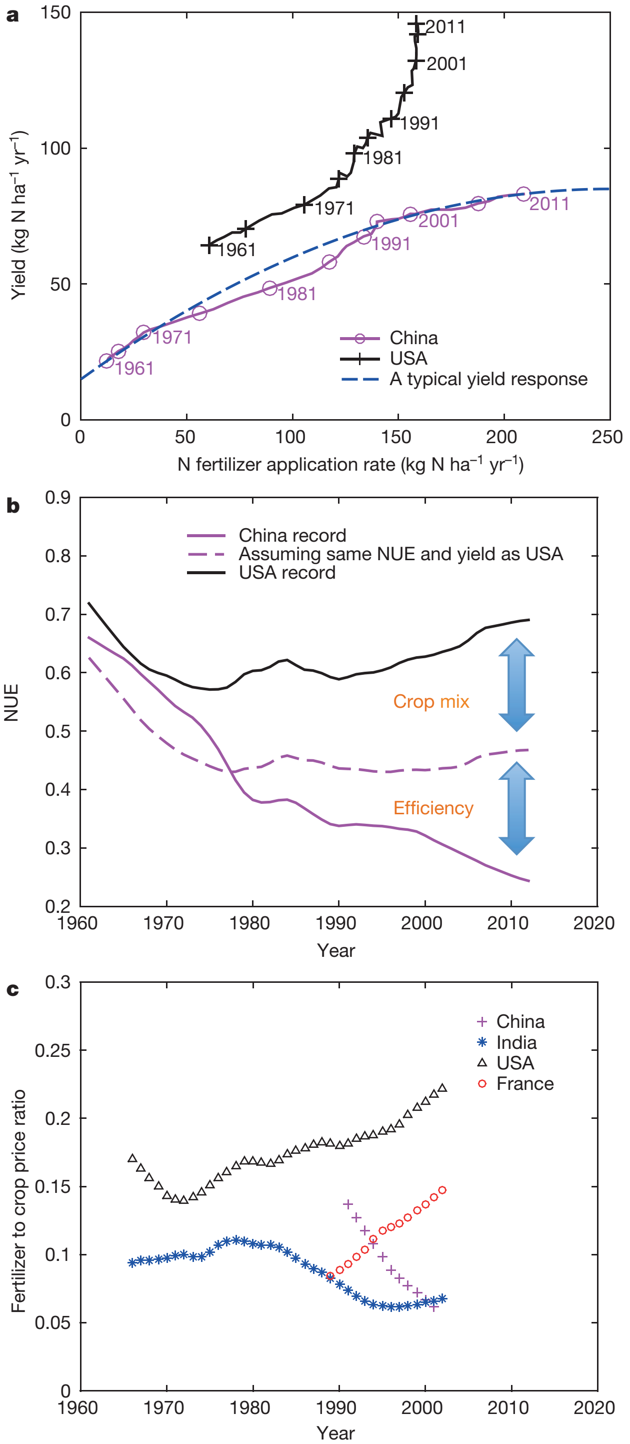

Figure 4 | A comparison of historical trends. **a**, Nationally averaged annual fertilization rates and yields of maize in China and the USA. **b**, NUE averaged across crops in China and the USA. **c**, Fertilizer to crop price ratios for China, India, USA and France. The dashed blue line in **a** shows a typical yield response function for maize based on fertilizer response trials[33,63], which demonstrates diminishing return in yield as N inputs increase. Note that the historical trend for China follows a pattern similar to a typical yield response function, indicating that further increases in N application rates will result in diminishing yield returns in China. In contrast, maize yield has increased in the USA since 2001 without increasing nationally averaged N input rates, suggesting that the yield improvement has been achieved by adopting more efficient technologies or management practices that shift the yield response curve upwards[33]. The dashed pink line in **b** shows what the NUE in China would be if it achieved NUE values realized in the USA for all crops, but with the crop mix of China. The gap between the dashed pink line and the black line (USA record) is the difference in NUE between countries that is attributable to the differences in crop mixes. The fertilizer to crop price ratio shown in **c** is determined by the N price of urea divided by the N price of maize product (see section 1.6 in Supplementary Information for data sources and methodologies). The data are smoothed using a ten-year window.

choice of technologies and practices for nutrient management, all of which affect NUE and N_{sur} (ref. 33). We tested whether the influence of R_{fc} appears at the national level using two methods: one examines the correlation coefficient of R_{fc} and NUE for individual countries, and the other applies a fixed effects model to all data to test the correlation between R_{fc} and NUE with and without including GDP per capita and crop mix (see section 2.3 in Supplementary Information). Because both the fertilizer and crop prices are 'at the farm gate', they include the effects of government subsidies[35]. The results for maize, for which the most data are available, indicate that the fertilizer to maize price ratio is positively correlated with NUE using both statistical approaches (Supplementary Table 12). We also found that maize prices are linearly correlated with the prices of most major crops, so we infer that the fertilizer to maize price ratio is likely to be a good index for the long-term trend of R_{fc} for all crops. Indeed, we found a statistically significant ($P < 0.001$) positive correlation between historical values of R_{fc} for maize and the NUE aggregated for all other crops. Moreover, this correlation is still statistically significant ($P < 0.001$) after adjusting for the effect of GDP per capita and crop mix (Supplementary Table 11).

Increases in R_{fc} since the 1990s, in both France and the USA (Fig. 4c), coincided with increases in NUE (ref. 57) and may have affected the EKC turning point. At the other extreme, both China and India have had declining values of R_{fc} (Fig. 4c), owing to heavily subsidized fertilizer prices[25,66]. Fertilizer subsidies reached US$18 billion in China in 2010 (ref. 66). Rates of N inputs have now reached levels of diminishing returns for crop yield in China (Fig. 4a), and China has the largest N_{sur} and one of the lowest nationally averaged NUE values in the world (Table 1). The very low R_{fc} in China incentivizes farmers to attempt to increase crop yield by simply adding more N or by choosing more N-demanding cropping systems (for example, change from cereal production to greenhouse vegetable production[67]) instead of adopting more N-efficient technologies and management practices.

Not all fertilizer subsidies are inappropriate. Where infrastructure for producing and transporting fertilizers is poor, as is the case for most of Africa, the cost can be so high that fertilizer use is prohibitively expensive for smallholder farmers, resulting in low yield and small, even negative N_{sur} (soil mining). In these cases, there is room for fertilizer subsidies to increase N inputs, because significant increases in N inputs could be absorbed and greatly increase crop yields without much immediate risk of N pollution[68–70]. When properly designed, temporary fertilizer subsidies structured to build up the private delivery network and with a built-in exit strategy can be an appropriate step[71]. The longer-term question for these countries will be whether they can 'tunnel through' the EKC by shifting crop production directly from a low-yield, high-NUE status to a high-yield, high-NUE status. This shift will require leapfrogging over the historical evolution of agricultural management practices by employing technologies and management practices that promote high NUE before N_{sur} grows to environmentally degrading levels. Acquiring and deploying such technologies, such as improved seed, balanced nutrient amendments, and water management, will require investments in technology transfer and capacity building.

Importance of crop mix

Another factor that may confound EKC trajectories is the mix of crops countries grow over time, which is affected by both demand and trade policies[72]. For example, changing patterns of crop mixes help to explain some of the differences between China and the USA. Since the 1990s an increasing percentage of agricultural land in China has been devoted to fruit and vegetable production, and N application to fruits and vegetables

Table 1 | N budget and NUE in crop production by region and crop in 2010 and projected for 2050

	Current (2010)				Projected (2050)			
	Harvest N ($Tg\,N\,yr^{-1}$)	Input N ($Tg\,N\,yr^{-1}$)	NUE	Surplus N ($Tg\,N\,yr^{-1}$)	Projected harvest N* ($Tg\,N\,yr^{-1}$)	Target NUE	Required input N ($Tg\,N\,yr^{-1}$)	Resulting surplus N ($Tg\,N\,yr^{-1}$)
By region†								
China	13	51	0.25	38	16	0.60	27	11
India	8	25	0.30	18	11	0.60	19	8
USA and Canada	14	21	0.68	7	19	0.75	25	6
Europe	7	14	0.52	7	10	0.75	13	3
Former Soviet Union	4	6	0.56	3	6	0.70	8	2
Brazil	6	11	0.53	5	10	0.70	15	4
Latin America (except Brazil)	7	12	0.52	6	10	0.70	15	4
Middle East and North Africa	3	5	0.48	3	4	0.70	5	2
Sub-Saharan Africa	4	5	0.72	2	9	0.70	13	4
Other OECD countries	1	2	0.52	1	2	0.70	2	1
Other Asian countries	8	19	0.41	11	10	0.60	17	7
Total	74	174	0.42	100	107	0.67	160	52
By crop type‡								
Wheat	13	30	0.42	17	18	0.70	25	8
Rice	11	29	0.39	18	14	0.60	23	9
Maize	13	28	0.46	15	19	0.70	28	8
Other cereal crops	5	9	0.53	4	7	0.70	11	3
Soybean	16	20	0.80	4	24	0.85	28	4
Oil palm	1	1	0.46	1	1	0.70	2	1
Other oil seed	4	10	0.43	6	8	0.70	11	3
Cotton	2	5	0.37	3	3	0.70	5	1
Sugar crops	1	5	0.19	4	2	0.40	4	2
Fruits and vegetables	3	25	0.14	21	5	0.40	11	7
Other crops	5	11	0.41	7	7	0.70	10	3
Total	74	174	0.42	100	107	0.68	157	50

The 2010 record is aggregated from our N budget database (see Supplementary Information section 1 for detailed methodologies and data sources used in developing this database). The 2050 projected harvest N is derived from a FAO projection of crop production to meet a scenario of global food demand[3]. The calculated target NUE values for 2050 are not meant to be prescriptive for particular countries or crops; rather, they are presented to illustrate the types of NUE values that would be needed, given this assumption of food demand[3], while limiting N_{sur} to near the lower bound ($50\,Tg\,N\,yr^{-1}$) of allowable N pollution estimated in planetary boundary calculations[78]. Harvest N, input N and surplus N values are rounded to the nearest $Tg\,N\,yr^{-1}$.
*The projected harvest N is based on an FAO scenario[3] for 2050 that assumes a world population of 9.1 billion people and increases in average caloric consumption to 3,200 kcal per capita in Latin America, China, the near East and north Africa, and an increase to 2,700 kcal per capita in sub-Saharan Africa and India. Consumption of animal products increases in developing countries, but differences between regions remain.
†The definitions of the country groups are in Supplementary Table 13.
‡The crop group is defined according to the International Fertilizer Industry Association's report on fertilizer use by crop[38].

now accounts for about 30% of total fertilizer consumption[38,73], with an average NUE of only about 0.10 (which is below the globally averaged NUE for fruits and vegetables of 0.14, and well below the global averages for other major crops; Table 1)[74,75]. At the same time, China has been increasingly relying on imported soybeans, an N-fixing crop that has very low N_{sur} (Table 1)[76]. In contrast, US soybean production has been growing and now accounts for about 30% of the harvested area for crop production (excluding land devoted to production of grasses or crops for feeding livestock) in the USA. While fertilizer subsidies in China probably account for much of the low NUE there, our analysis shows that the difference in crop mix also accounts for nearly half of the NUE difference between China and USA (Fig. 4b).

To address this issue globally, we tested the relationship between NUE and the fraction of harvested area for fruits and vegetables with a fixed effects model for the 113 countries (Supplementary Table 11). The fraction of harvested area for fruit and vegetable production negatively correlates with NUE, and that relationship is still significant ($P < 0.001$) even after adjusting for the effect of GDP per capita.

Meeting the growing challenge

Agriculture is currently facing unprecedented challenges globally. On one hand, crop production needs to increase by about 60%–100% from 2007 to 2050 to meet global food demand[3,77–79]. On the other hand, anthropogenic reactive N input to the biosphere has already exceeded a proposed planetary boundary[5,80], and the increasing demand for food and biofuel is likely to drive up N inputs even further. Therefore, it is critical to establish global and national goals for N use in crop production and to use those goals as reference points to evaluate progress made and guide NUE improvement.

Global and national goals

The planetary boundary for human use of reactive N that can be tolerated without causing unsustainable air and water pollution has been defined in mainly two ways: (1) as the maximum allowable amount of anthropogenic newly fixed N in agriculture that can be introduced into the earth system ($62–82\,Tg\,N\,yr^{-1}$)[5,80], and (2) as the maximum allowable N_{sur} released from agricultural production to the environment.

Calculations of planetary boundaries according to the first definition require assumptions about nutrient-use efficiency in agriculture. As NUE increases, more N inputs would be manageable while still remaining within air and water pollution limits because more applied N would be taken up by harvested crops. Therefore, rather than focusing on a planetary boundary of allowable newly fixed N, which varies depending on the NUE assumption, we follow the second approach, by estimating what NUE would be needed to produce the food demand

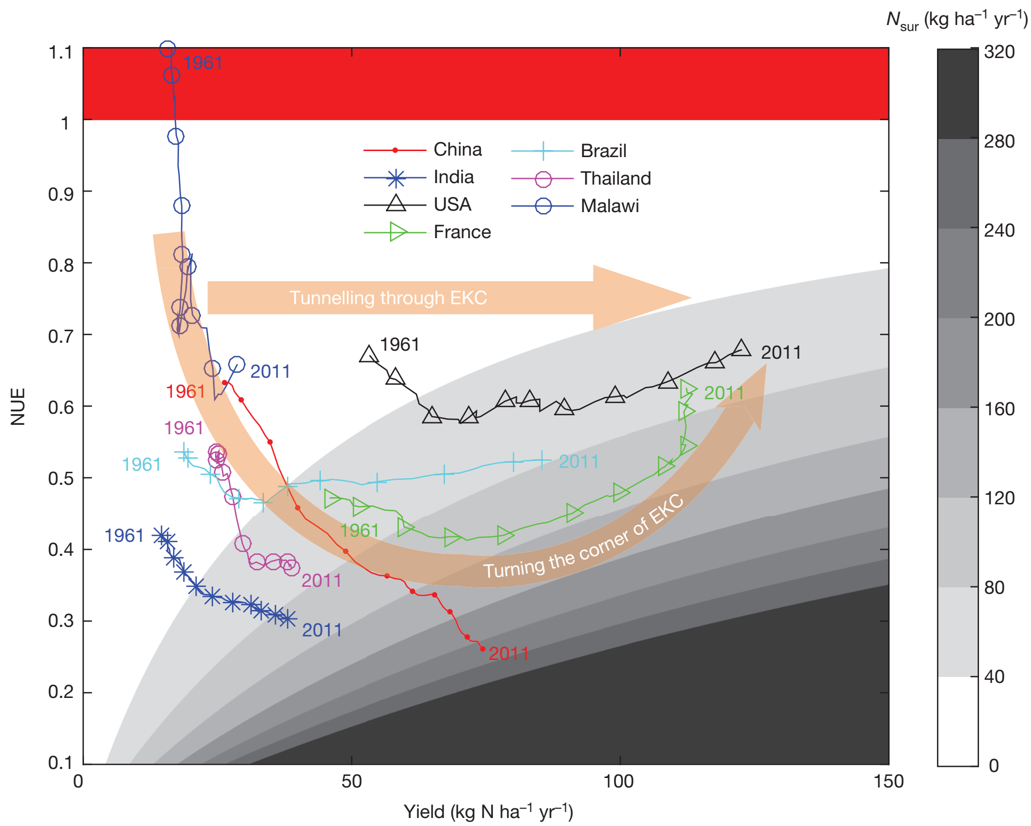

Figure 5 | Historical trends of N_{yield}, NUE and N_{sur}, for a sample of countries examined in this study. The greyscale shows the level of N_{sur}. The area covered in red indicates negative N_{sur}, where the crop production is mining soil N. The data have been smoothed by ten years to limit the impact of year-to-year variation in weather conditions. Curves moving towards the lower right indicate that those countries are achieving yield increases by sacrificing NUE and increasing N_{sur}, whereas curves moving towards the upper right indicate countries achieving yield increases by increasing NUE and resulting in steady or decreasing N_{sur}.

projected for 2050 (ref. 3; Table 1) while keeping N_{sur} within the bounds estimated for acceptable air and water quality. Over 60% of N pollution is estimated to originate from crop production[78], so this is the primary sector that must be addressed to reduce N pollution. From an analysis of the implications of N cycling in several "shared socio-economic pathways"[81], Bodirsky *et al.* (ref. 78) calculated that global agricultural N_{sur} should not exceed about 50–100 Tg N yr^{-1}. Therefore, we use 50 Tg N yr^{-1} as an estimate of the global limit of N_{sur} from crop production.

Meeting the 2050 food demand of 107 Tg N yr^{-1} projected by the Food and Agriculture Organization (FAO, ref. 3) while reducing N_{sur} from the current 100 Tg N yr^{-1} to a global limit of 50 Tg N yr^{-1} (ref. 78) requires very large across-the-board increases in NUE. Globally, NUE would increase from ~0.4 to ~0.7, while the crop yield would increase from 74 Tg N yr^{-1} to 107 Tg N yr^{-1} (Table 1). Recognizing regional differences in crop production and development stage, this average could be achieved if average NUE rose to 0.75 in the EU and USA, to 0.60 in China and the rest of Asia (assuming they continue to have a high proportion of fruits and vegetables in their crop mix), and to 0.70 in other countries, including not dropping below 0.70 in sub-Saharan Africa as it develops (Table 1). Similarly, NUE targets could be established for individual crops, such as improving the global average from 0.14 to 0.40 for fruits and vegetables, and increasing the global average NUE for maize from 0.50 to 0.70 (Table 1).

The challenges in achieving these ambitious goals differ among countries. Figure 5 shows the trajectories of major crop producing countries on the yield–NUE map for the last five decades. The *x* and *y* axes show the two efficiency terms in crop production, NUE and N_{yield}, while the greyscale displays N_{sur}. To compare the nationally averaged field-scale (in units of kg N ha^{-1} yr^{-1}) N_{sur} in Fig. 5 to a global limit of 50–100 Tg N yr^{-1}, the global average N_{sur} target would need to be 39–78 kg N ha^{-1} yr^{-1} across the 2010 harvested area of 1.3 billion hectares. For the examples shown, the USA, France, and Brazil appear to be on this trajectory, although further progress is still needed. In contrast, China and India not only have not yet found an EKC turning point, but also have much ground to make up to reduce their N_{sur} once they turn the corner on their EKC. Although a great challenge, this could also be seen as an opportunity to reduce fertilizer expenditures while increasing agricultural productivity. Malawi, like many sub-Saharan African countries and other least developed countries, has been on a classic downward trajectory of decreasing NUE as it has started to increase N inputs, although evidence from recent years suggests that this decline may have reversed, which would be a necessary first step to tunnelling through the EKC (Fig. 5).

Achieving NUE targets

Achieving ambitious NUE targets while also increasing yields to meet future food demands requires implementation of technologies and management practices at the farm scale, which has been described widely and in considerable detail in the agricultural, environmental, and development literature[17]. Some common principles include the '4Rs' approach of applying the right source, at the right rate, at the right time, in the right place[34]. However, the technologies and management practices needed to achieve the 4Rs vary regionally depending on the local cropping systems, soil types, climate and socio-economic situations. Where improvements in plant breeding, irrigation, and application of available 4R technologies have already made large gains, new technological developments may be needed to achieve further gains, such as more affordable slow-release fertilizers, nitrification and urease inhibitors, fertigation (that is, applying fertilizer via irrigation water), and high-tech approaches to precision agriculture[58].

It is promising that the development and the combination of information technology, remote sensing, and ground measurements will make information about precision farming more readily available, accessible, affordable and site-specific[82]. In many cases, large gains could still be made with more widespread adoption of existing technologies, but a myriad of social and economic factors affecting farmer decision-making regarding nutrient management have only recently begun to receive attention and are critical in improving NUE (ref. 15). Socio-economic impediments, often related to cost and perceived risk, as well as lack of trust in recommendations by agricultural extension agents, often discourage farmers from adopting improved nutrient management practices[59,60,83,84]. Experience has shown that tailoring regulations, incentives, and outreach to local conditions, administered and enforced by local entities, and supported by trust established among local stakeholders improve the success of efforts designed to increase NUE (ref. 15).

Although much of the work must be done at the farm scale, there are important policies that should be implemented on national and multi-national scales. First, improving NUE should be adopted as one of the indicators of the Sustainable Development Goals[16] and should be used in conjunction with crop yield and perhaps other soil health parameters to measure the sustainability of agricultural development. To report reliably on a NUE indicator, countries should be strongly encouraged to collect data routinely on their N management in crop and livestock production. These data should be used to trace trajectories of the three indices of agricultural N pollution, agricultural efficiency and food security targets (that is, N_{sur}, NUE and N_{yield}), as we have done here (Fig. 5) to demonstrate where progress is being made and where stronger local efforts are needed. The data used to construct Fig. 5 have served to demonstrate trends, but both improved data quality and international harmonization of data standards are needed. Regular attention should be given to these trends to establish national and local targets and policies. Just as protocols established by the Intergovernmental Panel on Climate Change permit nations to gauge their progress and commitment for reducing greenhouse gas emissions, protocols for measuring and reporting on a Sustainable Development Goal pertaining to NUE could enable governments to assess their progress in achieving food security goals while maintaining environmental quality.

Second, nutrient management in livestock operations and human dietary choices needs more attention. Here we have focused entirely on crop production, largely because of availability of data, but the N_{sur}, NUE and N_{yield} indices are equally important in livestock management[85]. Indeed, soybeans and some cereals have high NUE as crops, but when fed to livestock, efficient recycling of the N in manure is challenging, resulting in lower integrated NUE for the crop–livestock production system[86]. The crop production scenario used here for 2050 (Table 1) makes assumptions about future dietary choices[3], which are beyond the scope of this study, but we note that future trends in diet will affect the demand for crop and livestock products, the crop mixes grown, and hence the NUE and N_{sur} of future agricultural systems[72].

Third, a similar approach to efficiency analysis would also be valuable for phosphorus (P) fertilizer management, interactions of N and P management, and reducing both N and P loading into aquatic ecosystems[87–90].

Fourth, national and international communities should facilitate technology transfer and promote agricultural innovation. Stronger international collaborations and investments in research, extension and human resources are urgently needed so that knowledge and experience can be shared, creating political and market environments that help to incentivize the development and implementation of more efficient technologies. Technology transfer and capacity building will be needed to enable sub-Saharan African countries to tunnel through the EKC (Fig. 5).

These solutions to improving NUE will require cross-disciplinary and cross-sectorial partnerships, such as: (1) integrating research and development of innovative agricultural technology and management systems with socio-economic research and the outreach needed for such innovations to be socially and economically viable and readily adopted by farmers; (2) analysing the nexus of food, water, nutrients and energy management to avoid pollution swapping (a measure designed to address one pollution problem leads to another; for example, retaining crop residues can reduce nitrogen runoff, but may lead to higher N_2O emission[91]) and to optimize the net benefits to farmers, the environment and society; (3) promoting knowledge and data sharing among private and public sectors to advance science-based nutrient management; and (4) training the next generation of interdisciplinary agronomic and environmental scientists equipped with broad perspectives and skills pertaining to food, water, energy and environment issues.

The EKC has often been described as an optimist's view of a world with declining environmental degradation. Here we have shown that there is evidence—indeed, there is hope—for the EKC pattern of declining N pollution with improving efficiencies in agriculture. However, we have also shown that continuation of the progress made so far is neither inevitable nor is it sufficient to achieve the projected 2050 goals of both food security and environmental stewardship. Turning points and trajectories of national agricultural EKCs will depend largely on agricultural, economic, environmental, educational and trade policies, and these will largely dictate the food and pollution outputs of future agriculture.

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1. Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z. & Winiwarter, W. How a century of ammonia synthesis changed the world. *Nature Geosci.* **1,** 636–639 (2008).
2. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478,** 337–342 (2011).
3. Alexandratos, N. & Bruinsma, J. *World Agriculture towards 2030/2050: the 2012 Revision*. Agricultural Development Economics Division of the Economic and Social Development Department Working Paper No. 12-03, http://www.fao.org/docrep/016/ap106e/ap106e.pdf (Food and Agriculture Organization of the United Nations, 2012).
4. Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490,** 254–257 (2012).
5. Steffen, W. *et al.* Planetary boundaries: guiding human development on a changing planet. *Science* **347,** 6223 (2015).
This paper provides the most recent updates on the research under the planetary boundaries framework.
6. Galloway, J. N. *et al.* The nitrogen cascade. *Bioscience* **53,** 341–356 (2003).
This is a classic paper on the many interacting environmental impacts of reactive forms of N as they move through the biosphere.
7. Galloway, J. N. *et al.* Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* **320,** 889–892 (2008).
8. Reay, D. S. *et al.* Global agriculture and nitrous oxide emissions. *Nature Clim. Change* **2,** 410–416 (2012).
9. Griffis, T. J. *et al.* Reconciling the differences between top-down and bottom-up estimates of nitrous oxide emissions for the U.S. corn belt. *Glob. Biogeochem. Cycles* **27,** 746–754 (2013).
10. Avnery, S., Mauzerall, D. L., Liu, J. & Horowitz, L. W. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmos. Environ.* **45,** 2284–2296 (2011).
11. Robertson, G. P. *et al.* Nitrogen–climate interactions in US agriculture. *Biogeochemistry* **114,** 41–70 (2013).
12. Jerrett, M. *et al.* Long-term ozone exposure and mortality. *N. Engl. J. Med.* **360,** 1085–1095 (2009).
13. Sanchez, P. A. & Swaminathan, M. Hunger in Africa: the link between unhealthy people and unhealthy soils. *Lancet* **365,** 442–444 (2005).
14. Cassman, K. G., Dobermann, A., Walters, D. T. & Yang, H. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu. Rev. Environ. Resour.* **28,** 315–358 (2003).
15. Davidson, E. A., Suddick, E. C., Rice, C. W. & Prokopy, L. S. More food, low pollution (Mo Fo Lo Po): a grand challenge for the 21st century. *J. Environ. Qual.* **44,** 305–311 (2015).
This paper reports outcomes of an interdisciplinary conference on the technical, social, and economic impediments to improving NUE in crop and animal production systems, and it introduces a series of papers addressing this issue.
16. Leadership Council of the Sustainable Development Solutions Network (SDSN). *Indicators and a Monitoring Framework for Sustainable Development Goals—Revised Working Draft, 16 January 2015*. http://unsdsn.org/resources (SDSN, 2015).
17. Newell Price, J. *et al. An Inventory of Mitigation Methods and Guide to their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture*. http://www.avondtc.org.uk/Portals/0/Farmscoper/DEFRA%20user%20guide.pdf (Defra Project WQ0106, ADAS and Rothamsted Research North Wyke, 2011).

18. Dinda, S. Environmental Kuznets curve hypothesis: a survey. *Ecol. Econ.* **49,** 431–455 (2004).
19. Grossman, G. M. & Krueger, A. B. Economic growth and the environment. *Q. J. Econ*. **110,** 353–377 (1995).
This was among the first set of studies to provide empirical evidence for the EKC hypothesis.
20. Arrow, K. *et al.* Economic growth, carrying capacity, and the environment. *Science* **15,** 91–95 (1995).
21. Panayotou, T. *Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development*. Working Paper 238 (Technology and Employment Programme, International Labour Organization, 1993).
22. Cole, M. A., Rayner, A. J. & Bates, J. M. The environmental Kuznets curve: an empirical analysis. *Environ. Dev. Econ.* **2,** 401–416 (1997).
23. Brock, W. A. & Taylor, M. S. Economic growth and the environment: a review of theory and empirics. *Handbk Econ. Growth* **1,** 1749–1821 (2005).
24. Li, F., Dong, S., Li, F. & Yang, L. Is there an inverted U-shaped curve? Empirical analysis of the environmental Kuznets curve in agrochemicals. *Front. Environ. Sci. Eng*. 1–12 (2014).
25. Singh, A. P. & Narayanan, K. Impact of economic growth and population on agrochemical use: evidence from post-liberalization India. *Environ. Dev. Sustain*. 1–17 (2015).
26. van Beek, C., Brouwer, L. & Oenema, O. The use of farmgate balances and soil surface balances as estimator for nitrogen leaching to surface water. *Nutr. Cycl. Agroecosyst.* **67,** 233–244 (2003).
27. Van Groenigen, J., Velthof, G., Oenema, O., Van Groenigen, K. & Van Kessel, C. Towards an agronomic assessment of N_2O emissions: a case study for arable crops. *Eur. J. Soil Sci.* **61,** 903–913 (2010).
28. Bouwman, L. *et al.* Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proc. Natl Acad. Sci. USA* **110,** 20882–20887 (2013).
29. Liu, J. *et al.* A high-resolution assessment on global nitrogen flows in cropland. *Proc. Natl Acad. Sci. USA* **107,** 8035–8040 (2010).
30. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* **9,** 105011 (2014).
This paper presents the 50-year trend of NUE and the yield response to N input on a country scale.
31. Conant, R. T., Berdanier, A. B. & Grace, P. R. Patterns and trends in nitrogen use and nitrogen recovery efficiency in world agriculture. *Glob. Biogeochem. Cycles* **27,** 558–566 (2013).
This study creates a global N input database by country and several major crops and found no convergence in N use among countries.
32. Brouwer, F. Nitrogen balances at farm level as a tool to monitor effects of agri-environmental policy. *Nutr. Cycl. Agroecosyst.* **52,** 303–308 (1998).
33. Zhang, X., Mauzerall, D. L., Davidson, E. A., Kanter, D. R. & Cai, R. The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. *J. Environ. Qual.* **44,** 312–324 (2015).
This paper develops a bioeconomic model to examine how technological and socioeconomic factors influence farming decisions and the resulting environmental impact.
34. Snyder, C., Davidson, E., Smith, P. & Venterea, R. Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions. *Curr. Opin. Environ. Sustain*. **9–10,** 46–54 (2014).
35. Food and Agriculture Organization of the United Nations. *FAOSTAT Online Database* http://faostat.fao.org/ (2015).
36. World Bank Group. *World Development Indicators 2012* http://data.worldbank.org/sites/default/files/wdi-2012-ebook.pdf (World Bank Publications, 2012).
37. Lassaletta, L. *et al.* Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry* **118,** 225–241 (2014).
38. Heffer, P. *Assessment of Fertilizer Use by Crop at the Global Level*. http://www.fertilizer.org/Library (International Fertilizer Industry Association, 2009).
39. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cycles* **22,** 1–19 (2008).
40. Herridge, D. F., Peoples, M. B. & Boddey, R. M. Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* **311,** 1–18 (2008).
41. Jayanthakumaran, K., Verma, R. & Liu, Y. CO_2 emissions, energy consumption, trade and income: a comparative analysis of China and India. *Energy Policy* **42,** 450–460 (2012).
42. He, J. & Wang, H. Economic structure, development policy and environmental quality: An empirical analysis of environmental Kuznets curves with Chinese municipal data. *Ecol. Econ.* **76,** 49–59 (2012).
43. Al-Mulali, U., Saboori, B. & Ozturk, I. Investigating the environmental Kuznets curve hypothesis in Vietnam. *Energy Policy* **76,** 123–131 (2015).
44. Alam, M. S. & Kabir, N. Economic growth and environmental sustainability: empirical evidence from East and South-East Asia. *Int. J. Econ. Finance* **5,** 86–97 (2013).
45. Diao, X., Zeng, S., Tam, C. M. & Tam, V. W. EKC analysis for studying economic growth and environmental quality: a case study in China. *J. Clean. Prod.* **17,** 541–548 (2009).
46. Song, M.-L., Zhang, W. & Wang, S.-H. Inflection point of environmental Kuznets curve in mainland China. *Energy Policy* **57,** 14–20 (2013).
47. Wagner, M. The carbon Kuznets curve: a cloudy picture emitted by bad econometrics? *Resour. Energy Econ.* **30,** 388–408 (2008).
48. Müller-Fürstenberger, G. & Wagner, M. Exploring the environmental Kuznets hypothesis: theoretical and econometric problems. *Ecol. Econ.* **62,** 648–660 (2007).
49. Chow, G. C. & Li, J. Environmental Kuznets curve: conclusive econometric evidence for CO_2. *Pac. Econ. Rev.* **19,** 1–7 (2014).
50. Pesaran, M. H., Shin, Y. & Smith, R. J. Bounds testing approaches to the analysis of level relationships. *J. Appl. Econ.* **16,** 289–326 (2001).
51. Wagner, M. The environmental Kuznets curve, cointegration and nonlinearity. *J. Appl. Econ*. **30,** 948–967 (2015).
52. Wagner, M. & Hong, S. H. Cointegrating polynomial regressions: fully modified OLS estimation and inference. *Econom. Theory*, http://dx.doi.org/10.1017/S0266466615000213 (2015).
53. Stern, D. I. The rise and fall of the environmental Kuznets curve. *World Dev.* **32,** 1419–1439 (2004).
54. Cavlovic, T. A., Baker, K. H., Berrens, R. P. & Gawande, K. A meta-analysis of environmental Kuznets curve studies. *Agric. Res. Econ. Rev.* **29,** 32–42 (2000).
55. Sutton, M. A. *et al.* (eds) *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives* (Cambridge Univ. Press, 2011).
56. van Grinsven, H. *et al.* Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive: a benchmark study. *Biogeosciences* **9,** 5143–5160 (2012).
57. van Grinsven, H. J. *et al.* Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050. *J. Environ. Qual.* **44,** 356–367 (2015).
58. Ferguson, R. B. Groundwater quality and nitrogen use efficiency in Nebraska's Central Platte River valley. *J. Environ. Qual.* **44,** 449–459 (2015).
59. Osmond, D. L., Hoag, D. L., Luloff, A. E., Meals, D. W. & Neas, K. Farmers' use of nutrient management: lessons from watershed case studies. *J. Environ. Qual.* **44,** 382–390 (2015).
60. Perez, M. R. Regulating farmer nutrient management: a three-state case study on the Delmarva Peninsula. *J. Environ. Qual.* **44,** 402–414 (2015).
61. International Fertilizer Industry Association (IFA). *The Global "4R" Nutrient Stewardship Framework. Developing Fertilizer Best Management Practices for Delivering Economic, Social, and Environmental Benefits*. AgCom/09/44, http://www.fertilizer.org/Library (IFA Task Force on Fertilizer Best Management Practices, IFA, 2009).
62. Davidson, E., Galloway, J., Millar, N. & Leach, A. N-related greenhouse gases in North America: innovations for a sustainable future. *Curr. Opin. Environ. Sust.* **9–10,** 1–8 (2014).
63. Sawyer, J. E. *et al. Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn*. http://www.extension.iastate.edu/publications/pm2015.pdf (Iowa State University Extension, 2006).
64. Robertson, G. P. & Vitousek, P. M. Nitrogen in agriculture: balancing the cost of an essential resource. *Annu. Rev. Environ. Resour.* **34,** 97–125 (2009).
65. Setiyono, T. D. *et al.* Maize-N: a decision tool for nitrogen management in maize. *Agron. J.* **103,** 1276–1283 (2011).
66. Li, Y. *et al.* An analysis of China's fertilizer policies: impacts on the industry, food security, and the environment. *J. Environ. Qual.* **42,** 972–981 (2013).
67. Ju, X., Kou, C., Christie, P., Dou, Z. & Zhang, F. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* **145,** 497–506 (2007).
68. Hickman, J. E., Tully, K. L., Groffman, P. M., Diru, W. & Palm, C. A. A potential tipping point in tropical agriculture: avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya. *J. Geophys. Res. Biogeosci*. **120,** 938–951 (2015).
69. Hickman, J. E., Havlikova, M., Kroeze, C. & Palm, C. A. Current and future nitrous oxide emissions from African agriculture. *Curr. Opin. Environ. Sust.* **3,** 370–378 (2011).
70. Zhou, M. *et al.* Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives. *Environ. Res. Lett.* **9,** 105009 (2014).
71. Jayne, T. S. & Rashid, S. Input subsidy programs in sub-Saharan Africa: a synthesis of recent evidence. *Agric. Econ.* **44,** 547–562 (2013).
72. Billen, G., Lassaletta, L. & Garnier, J. A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade. *Environ. Res. Lett.* **10,** 025001 (2015).
73. Heffer, P. *Assessment of Fertilizer Use by Crop at the Global Level 2010–2010/11*. http://www.fertilizer.org/En/Statistics/Agriculture_Committee_Databases.aspx (International Fertilizer Industry Association, 2013).
74. Shi, W.-M., Yao, J. & Yan, F. Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. *Nutr. Cycl. Agroecosyst.* **83,** 73–84 (2009).
75. Ju, X.-T. *et al.* Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl Acad. Sci. USA* **106,** 3041–3046 (2009).
76. Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396,** 262–265 (1998).
77. Searchinger, T. *et al. Creating a Sustainable Food Future: a Menu of Solutions to Sustainably Feed more than 9 billion people by 2050*. World Resources Report 2013-14, Interim Findings (World Resources Institute, 2013).

78. Bodirsky, B. L. *et al.* Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Commun*. **5,** 3858 (2014).
79. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108,** 20260–20264 (2011).
80. de Vries, W., Kros, J., Kroeze, C. & Seitzinger, S. P. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr. Opin. Environ. Sustain*. **5,** 392–402 (2013).
81. Nakicenovic, N. & Swart, R. *Special Report on Emissions Scenarios* (eds Nakicenovic, N. & Swart, R.) Vol. 1, 1–612 (Cambridge Univ. Press, 2000).
82. Mulla, D. J. Twenty five years of remote sensing in precision agriculture: key advances and remaining knowledge gaps. *Biosystems Eng.* **114,** 358–371 (2013).
83. David, M. B. *et al.* Navigating the socio-bio-geo-chemistry and engineering of nitrogen management in two Illinois tile-drained watersheds. *J. Environ. Qual.* **44,** 368–381 (2014).
84. Weber, C. & McCann, L. Adoption of nitrogen-efficient technologies by US corn farmers. *J. Environ. Qual.* **44,** 391–410 (2014).
85. Powell, J., Gourley, C., Rotz, C. & Weaver, D. Nitrogen use efficiency: a potential performance indicator and policy tool for dairy farms. *Environ. Sci. Policy* **13,** 217–228 (2010).
86. Powell, J. & Rotz, C. Measures of nitrogen use efficiency and nitrogen loss from dairy production systems. *J. Environ. Qual.* **44,** 336–344 (2015).
87. MacDonald, G. K., Bennett, E. M., Potter, P. A. & Ramankutty, N. Agronomic phosphorus imbalances across the world's croplands. *Proc. Natl Acad. Sci. USA* **108,** 3086–3091 (2011).
88. MacDonald, G. K., Bennett, E. M. & Taranu, Z. E. The influence of time, soil characteristics, and land-use history on soil phosphorus legacies: a global meta-analysis. *Glob. Change Biol.* **18,** 1904–1917 (2012).
89. Cordell, D., Drangert, J.-O. & White, S. The story of phosphorus: global food security and food for thought. *Glob. Environ. Change* **19,** 292–305 (2009).
90. Schoumans, O. *et al.* Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. *Sci. Total Environ.* **468–469,** 1255–1266 (2014).
91. Stevens, C. J. & Quinton, J. N. Diffuse pollution swapping in arable agricultural systems. *Crit. Rev. Environ. Sci. Technol.* **39,** 478–520 (2009).

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