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1 **Managing nitrogen for sustainable development**

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18 **Preface**

19 Improvements in nitrogen use efficiency (NUE) in crop production are critical for
20 addressing the triple challenges of food security, environmental degradation, and
21 climate change. Such improvements depend not only on technological innovation,
22 but also on poorly understood socio-economic factors. Here we analyze historical
23 patterns of agricultural NUE and find a broad range of national pathways of
24 agricultural development and related pollution. We estimate examples of NUE and
25 yield targets by geographic region and crop type required to meet global food
26 demand and environmental stewardship goals in 2050. Furthermore, we discuss
27 socio-economic policies and technological innovations that may help achieve them.
28

29 **The nitrogen challenge**

30 More than half the world's people are nourished by crops grown with
31 synthetic nitrogen (N) fertilizers, which were made possible in the early 20th
32 century by the invention of the Haber-Bosch process to reduce atmospheric
33 nitrogen gas (N₂) to reactive forms of N (ref. 1). A reliable supply of N and other
34 nutrients essential for plant growth have allowed farmers to greatly increase crop
35 production per unit land over the past 100 years, thus promoting economic
36 development, allowing larger populations, and sparing forests that would likely
37 otherwise have been converted to agriculture to meet food demand². Despite this
38 progress, nearly one billion people remain undernourished³. In addition, the global
39 population will increase by 2-3 billion by 2050, implying that demands for N
40 fertilizers and agricultural land are likely to grow substantially^{2,4}. While there are
41 many causes of undernourishment and poverty, careful N management will be
42 needed to nourish a growing population while minimizing adverse environmental
43 and health impacts.

44 Unfortunately, unintended adverse environmental and human health impacts
45 result from reactive N escaping agricultural soils, including groundwater
46 contamination, eutrophication of freshwater and estuarine ecosystems,
47 tropospheric pollution related to nitrogen oxides and ammonia gas emissions, and
48 accumulation of the potent greenhouse gas and stratospheric ozone depleting
49 substance, nitrous oxide⁵⁻⁹ (Fig. 1). Some of these environmental consequences,
50 such as climate change and tropospheric ozone pollution, can also negatively affect

51 crop yields^{10,11} and human health¹². Hence, too little N means lower crop
52 productivity, poor human nutrition, and soil degradation¹³, but too much N leads to
53 environmental pollution and its concomitant threats to agricultural productivity,
54 food security, ecosystem health, human health, and economic prosperity.

55 Improving nitrogen use efficiency (NUE), namely the fraction of N input
56 harvested as product, is one of the most effective means of increasing crop
57 productivity while decreasing environmental degradation^{14,15}. Indeed, NUE has
58 been proposed as an indicator for assessing progress in achieving the new
59 Sustainable Development Goals (SDGs)¹⁶. Fortunately, we have a large and growing
60 knowledge base and technological capacity for managing N in agriculture¹⁷, and
61 awareness is growing among both agricultural and environmental stakeholder
62 groups that N use is both essential and problematic¹⁵. This growing recognition
63 from multiple stakeholders and ongoing advances in agricultural technology are
64 creating a possible turning point where knowledge-based N management could
65 advance substantially throughout the world. However, improving NUE requires
66 more than technical knowledge. Poorly understood cultural, social, and economic
67 incentives for and impediments to farmer adoption of NUE technologies and best
68 management practices are also needed and are only beginning to receive
69 attention¹⁵.

70 Here we analyze historical patterns (1961 – 2011) of agricultural N use in
71 113 countries to demonstrate a broad range of pathways of socio-economic
72 development and related N pollution. Our analysis suggests that many countries
73 show a pattern similar to an Environmental Kuznets Curve (EKC), in which N

74 pollution first increases and then decreases with economic growth¹⁸⁻²¹. So far, most
75 EKC analyses have focused on pollution from industrial and transportation
76 sectors^{19,22,23}; the present study is one of few to consider agricultural N pollution in
77 the EKC context^{24,25}, and to apply it globally. However, the patterns of N pollution
78 are neither automatic nor inevitable. Socio-economic circumstances and policies
79 vary widely among countries, affecting factors such as fertilizer to crop price ratios
80 and crop mixes, which, as our analysis shows, influence the turning points of the
81 EKC. While technological and socio-economic opportunities for NUE improvement
82 vary regionally, our analysis shows that average global NUE in crop production
83 needs to improve from ~0.4 to ~0.7 to meet the dual goals of food security and
84 environmental stewardship in 2050.

85 **Patterns of nitrogen pollution**

86 As a useful indicator of potential losses of N to the environment from
87 agricultural soils^{26,27}, N surplus (N_{sur}) is defined as the sum of N inputs (fertilizer,
88 manure, biologically fixed N, and N deposition in kg N ha⁻¹ yr⁻¹) minus N outputs^{28,29}
89 (the N removed within the harvested crop products, N_{yield} in kg N ha⁻¹ yr⁻¹, Fig. 1).
90 Some of the N_{sur} recycles within the soil, but most N_{sur} is lost to the environment
91 over the long term, because the difference between annual inputs and outputs is
92 usually large relative to changes in soil N stocks. The related term of NUE, also
93 called the output-input ratio of N, is mathematically defined as the dimensionless
94 ratio of the sum of all N removed in harvest crop products (outputs or N_{yield})
95 divided by the sum of all N inputs to a cropland^{30,31} (Fig. 1). The N_{sur} , NUE, and

96 N_{yield} terms can serve as environmental pollution, agricultural efficiency, and food
97 security targets^{32,33}, respectively, which are inherently interconnected through their
98 mathematical definitions³³ and their real world consequences (Fig. 1).

99 ***Variable turning points on the Kuznets curve***

100 As an indicator of the extent of environmental degradation, N_{sur} aggregated
101 to a national average for all crops ($\text{kg N ha}^{-1} \text{ yr}^{-1}$) is closely related to income growth,
102 mainly in two contrasting pathways: On one hand, increasing income enables
103 demand for more food consumption³³, which drives up both production intensity
104 and extensity and consequently results in more N lost to the environment. On the
105 other hand, increasing income is often accompanied by a societal demand for
106 improved environmental quality, such as clean water and clean air, and is also
107 accompanied by access to advanced technology^{18,19}. Consequently, governments
108 may impose regulatory policies or offer subsidies and incentives targeted at
109 reducing local or regional N pollution, and farmers may adopt more efficient
110 technologies.

111 Therefore, we hypothesize that N_{sur} follows a pattern similar to the EKC:
112 N_{sur} increases with income growth and the quest for food security at early stages of
113 national agricultural development (first phase), but then decreases with further
114 income growth during a more affluent stage (second phase), eventually approaching
115 an asymptote determined by the theoretical limit of the NUE of the crop system
116 (third phase, Fig. 2). Sustainable intensification of agriculture has been advanced as
117 the key to achieving the second phase of the EKC, including use of cultivars best
118 adapted to the local soil and climate conditions, improved water management,

119 balancing N application with other nutrient amendments, precision timing and
120 placement of fertilizer and manure applications to meet crop demands, the use of
121 enhanced efficiency fertilizers, and support tools to calculate proper dosing^{14,17,34}.
122 While N_{sur} is the EKC environmental degradation indicator, the mathematical
123 relationship between N_{sur} and NUE results in nearly mirror images in Fig. 2
124 (although see Section 1 in Supplementary Information for a discussion of situations
125 in which N_{sur} and NUE can both increase simultaneously).

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

137 We tested the existence of a sustainable intensification phase (or an EKC
138 pattern) with a five-decade record (1961-2011) of N_{sur} and GDP per capita^{28,35-40}
139 with a fixed effects model⁴¹⁻⁴³ across 113 countries for which sufficient data were
140 available and a regression model for each individual country^{18,44-46}(See Sections 1
141 and 2 in Supplementary Information). The fixed effects model shows a significant

142 quadratic relationship between GDP per capita and N_{sur} ($p < 0.001$, Supplementary
143 Table 9). Regressions between GDP per capita and N_{sur} for each individual country
144 fall into five response types (examples of each group are shown in Fig. 3). Of the
145 113 countries, 56 countries (Group 1) show bell-shaped relationships between N_{sur}
146 and GDP per capita, indicating that N_{sur} increased and then leveled off or decreased
147 as economic development proceeded, as expected for an EKC (two examples are
148 illustrated in Fig. 3a). Those 56 countries account for about 87% of N fertilizer
149 consumption and about 70% of harvested area of all 113 countries. These data
150 provide support for an EKC pattern for N pollution from agriculture, although as we
151 show below, the potential causes of EKC shapes and turning points are complex.
152 Furthermore for 28 of the 56 countries, by 2011 the rate of increase in N_{sur} had only
153 slowed or leveled off and had not yet actually decreased, indicating likely but still
154 uncertain conformance with an EKC (Supplementary Tables 5 and 6).

155 Countries with a linear or accelerating increase in N_{sur} (Group 3 and most
156 countries in Group 2) as GDP per capita grew have not yet approached an EKC
157 turning point (e.g., Fig. 3b), but could still follow an EKC in the future as their N
158 input growth slows and NUE increases. Most countries showing an insignificant
159 relationship between N_{sur} and GDP per capita (Group 4) or with a negative N_{sur}
160 (Group 5) have had such little income growth and use so little N that the EKC
161 concept cannot be evaluated yet due to limited change in the country's GDP per
162 capita (e.g., Fig. 3b).

163 Classic empirical studies on EKC, such as Grossman and Krueger (ref. 19),
164 have been criticized due to concerns regarding statistical analyses of time series

165 data that may be non-stationary⁴⁷⁻⁴⁹. Therefore, we examined the stationarity of our
166 data (Supplementary Table 7) and used the Autoregressive Distributed Lag
167 modeling approach (ARDL)⁵⁰, which is the most frequently used method for the
168 cointegration test in EKC empirical studies published in the last decade⁴³, to test
169 cointegration on a subset of the data. The ARDL regression models showed the
170 same long-term relationships between N surplus and GDP per capita as presented
171 above for all tested countries (Supplementary Table 8). The application of the ARDL
172 method in EKC studies has also been criticized recently for including the quadratic
173 term in the cointegration test, and some new methods have been proposed^{51,52}.
174 Further evaluation is needed on the limitations and performance of the ARDL and
175 newly proposed methods for EKC analyses.

176 Another common criticism of the EKC concept is that the turning point for
177 transitioning to declining environmental degradation is highly variable among
178 pollutants and among countries^{18,53,54}. Consistent with those observations, no
179 specific value of GDP per capita was a good predictor of turning points for N_{sur} on
180 the EKC among countries in the present study. For example, N_{sur} in Germany and
181 France started to decline when GDP per capita reached about \$25,000 in the 1980s,
182 while N_{sur} in the USA leveled off and started to decline more recently when GDP per
183 capita reached about \$40,000. Our analysis also shows that countries have widely
184 different values of NUE and N_{sur} even when yields are similar. Some of this
185 variation is likely due to underlying biophysical conditions, such as rainfall
186 variability and soil quality, which influence crop choices, yield responses, and NUE.

187 However, cultural, social, technological, economic and policy factors also likely
188 affect the turning points on the EKC trajectory of each country.

189 The turning point in European Union (EU) countries appears to have been
190 driven at least in part by policies⁵⁵. Beginning in the late 1980s and through the
191 early 2000s, increases in NUE and decreases in N_{sur} in several EU countries
192 coincided with changes in the EU Common Agricultural Policy, which reduced crop
193 subsidies, and adoption of the Nitrates Directive, which limited manure application
194 rates on cropland^{56,57}. Relying mostly on volunteer approaches in the USA, the
195 leveling off and modest decrease in N_{sur} since the 1990s is largely the result of
196 increasing crop yields while holding N inputs steady (Fig. 4a), which has resulted
197 from improved crop varieties, increased irrigation and other technological
198 improvements^{57,58}. A few state regulatory programs have required nutrient
199 management plans, placed limitations on fertilizer application dates and amounts,
200 and required soil and plant testing, with varying degrees of success⁵⁸⁻⁶⁰. Concerns
201 about water and air quality, estuarine hypoxic zones, stratospheric ozone depletion,
202 and climate change have also stimulated many outreach efforts by governments,
203 fertilizer industry groups, retailers, and environmental organizations to provide
204 farmers with information, training and innovative financial incentives to voluntarily
205 improve NUE (refs 15,59,61,62).

206 ***Fertilizer to crop price ratios***

207 Policy can impact NUE not only through regulation and outreach, but also by
208 affecting prices at the farm gate. The ratio of fertilizer to crop prices (R_{fc}) has been
209 widely used in combination with data on yield responses to fertilizer application to

210 advise farmers on fertilizer application rates that yield optimal economic returns⁶³⁻
211 ⁶⁵. In addition to influencing fertilizer application rates, R_{fc} also affects farmer
212 decisions regarding their choice of technologies and practices for nutrient
213 management, all of which affect NUE and N_{sur} (ref. 33). We tested whether the
214 influence of R_{fc} appears at the national level using two methods: one examines the
215 correlation coefficient of R_{fc} and NUE for individual countries, and the other applies
216 a fixed effects model to all data to test the correlation between R_{fc} and NUE with
217 and without considering GDP per capita and crop mix (see Section 2.3 in
218 Supplementary Information). Because both the fertilizer and crop prices are at the
219 farm gate, they include the effects of government subsidies³⁵. The results for maize,
220 for which the most data are available, indicate that the fertilizer to maize price ratio
221 is positively correlated with NUE using both statistical approaches (Supplementary
222 Table 12). We also found that maize prices are linearly correlated with prices of
223 most major crops, so we infer that the fertilizer to maize price ratio is likely a good
224 index for the long-term trend of R_{fc} for all crops. Indeed, we found a significant
225 positive correlation between historical values of R_{fc} for maize and the NUE
226 aggregated for all other crops. Moreover, this correlation is still significant after
227 adjusting for the effect of GDP per capita and crop mix (Supplementary Table 11).

228 Increases in R_{fc} since the 1990s, in both France and the USA (Fig. 4c),
229 coincided with increases in NUE (ref. 57) and may have affected the EKC turning
230 point. At the other extreme, both China and India have had declining values of R_{fc}
231 (Fig. 4c), owing to heavily subsidized fertilizer prices^{25,66}. Fertilizer subsidies

232 reached \$18 billion in China in 2010 (ref. 66). Rates of N inputs have now reached
233 levels of diminishing returns for crop yield in China (Fig. 4a), and China has the
234 largest N_{sur} and one of the lowest nationally averaged NUE values in the world
235 (Table 1). The very low R_{fc} in China incentivizes farmers to attempt to increase
236 crop yield by simply adding more N or by choosing more N-demanding cropping
237 systems (e.g. change from cereal production to greenhouse vegetable production⁶⁷)
238 instead of adopting more N-efficient technologies and management practices.

239 Not all fertilizer subsidies are inappropriate. Where infrastructure for
240 producing and transporting fertilizers is poor, as is the case for most of Africa, the
241 cost can be so high that fertilizer use is prohibitively expensive for small holder
242 farmers, resulting in low yield and small, even negative (soil mining) N surplus. In
243 these cases, there is room for fertilizer subsidies to increase N inputs, because
244 significant increases in N inputs could be absorbed and greatly increase crop yields
245 without much immediate risk of N pollution⁶⁸⁻⁷⁰. When properly drawn, temporary
246 fertilizer subsidies structured to build up the private delivery network and with a
247 built-in exit strategy can be an appropriate step⁷¹. The longer term question for
248 these countries will be whether they can “tunnel through” the EKC by shifting crop
249 production directly from a low-yield-high-NUE status to a high-yield-high-NUE
250 status. This shift will require leapfrogging over historical evolution of agricultural
251 management practices by employing technologies and management practices that
252 promote high NUE before N surpluses grow to environmentally degrading levels.
253 Acquiring and deploying such technologies, such as improved seed, balanced

254 nutrient amendments, and water management, will require investments in
255 technology transfer and capacity building.

256 ***Importance of crop mix***

257 Another factor that may confound EKC trajectories is the mix of crops
258 countries grow over time, which is affected by both demand and trade policies⁷².
259 For example, changing patterns of crop mixes help explain some of the differences
260 between China and the USA. Since the 1990s an increasing percentage of
261 agricultural land in China has been devoted to fruit and vegetable production, and N
262 application to fruits and vegetables now accounts for about 30% of total fertilizer
263 consumption^{38,73}, with an average NUE of only about 0.10 (which is below the
264 globally averaged NUE for fruits and vegetables of 0.14, and well below the global
265 averages for other major crops; Table 1)^{74,75}. At the same time, China has been
266 increasingly relying on imported soybeans, a N fixing plant that has very low N_{sur}
267 (Table 1)⁷⁶. By contrast, US soybean production has been growing and now
268 accounts for about 30% of the harvested area for crop production (excluding land
269 devoted to forage production) in the USA. While fertilizer subsidies in China likely
270 account for much of the low NUE there, our analysis shows that the difference in
271 crop mix also accounts for nearly half of the NUE difference between China and USA
272 (Fig. 4b).

273 To address this issue globally, we tested the relationship between NUE and
274 the fraction of harvested area for fruits and vegetables with a fixed effects model for
275 the 113 countries (Supplementary Table 11). The fraction of harvested area for

276 fruit and vegetable production negatively correlates with NUE, and that relationship
277 is still significant even after adjusting for the effect of GDP per capita.

278 **Meeting the growing challenge**

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

287 ***Global and national goals***

288 The planetary boundary for human use of reactive N that can be tolerated
289 without causing unsustainable air and water pollution has been defined in mainly
290 two ways: 1) as the maximum allowable amount of anthropogenic newly fixed N in
291 agriculture that can be introduced into the earth system (62-82 Tg N yr⁻¹)^{5,80}, and 2)
292 as the maximum allowable N surplus released from agricultural production to the
293 environment. Calculations of planetary boundaries according to the first definition
294 require assumptions about nutrient use efficiency in agriculture. As NUE increases,
295 more N inputs would be manageable while still remaining within air and water
296 pollution limits as more applied N would be taken up by harvested crops. Therefore,
297 rather than focusing on a planetary boundary of allowable newly-fixed-N, which

298 varies depending on the NUE assumption, we follow the second approach by
299 estimating what NUE would be needed to produce the food demand projected for
300 2050 (ref 3; Table 1) while keeping N_{sur} within bounds estimated for acceptable air
301 and water quality. Over 60% of N pollution is estimated to originate from crop
302 production⁷⁸, so this is the primary sector that must be addressed to reduce N
303 pollution. Based on an analysis of the implications of N cycling in several “shared
304 socio-economic pathways”⁸¹, Bodirsky et al. (ref. 78) calculated that global
305 agricultural N_{sur} should not exceed about 50-100 Tg N yr⁻¹. Thus we use 50 Tg N yr⁻¹
306 as an estimate of the global limit of N_{sur} from crop production.

307 Meeting the 2050 food demand of 107 Tg N yr⁻¹ projected by Food and
308 Agriculture Organization (FAO, ref. 3) while reducing N_{sur} from the current 100 Tg
309 N yr⁻¹ to a global limit of 50 Tg N yr⁻¹ (ref. 78) requires very large across-the-board
310 increases in NUE. Globally, NUE would increase from ~0.4 to ~0.7, while the crop
311 yield would increase from 74 to 107 Tg N yr⁻¹ (Table 1). Recognizing regional
312 differences in crop production and development stage, this average could be
313 achieved if average NUE rose to 0.75 in the EU and USA, to 0.60 in China and the rest
314 of Asia (assuming they continue to have a high proportion of fruits and vegetables in
315 their crop mix), and to 0.70 in other countries, including not dropping below 0.70 in
316 Sub-Saharan Africa as it develops (Table 1). Similarly, NUE targets could be
317 established for individual crops, such as improving the global average from 0.14 to
318 0.40 for fruits and vegetables, and increasing the global average NUE for maize from
319 0.50 to 0.70 (Table 1).

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

336 ***Achieving nitrogen use efficiency targets***

337 Achieving ambitious NUE targets while also increasing yields to meet future
338 food demands requires implementation of technologies and management practices
339 at the farm scale, which has been described widely and in considerable detail in the
340 agricultural, environmental, and development literature¹⁷. Some common
341 principles include the “4Rs” approach of applying the *right* source, at the *right* rate,
342 in the *right* time, at the *right* place³⁴. However, the appropriate technologies and

343 management practices to achieve the 4Rs vary regionally depending on the local
344 cropping systems, soil types, climate, and socio-economic situations. Where
345 improvements in plant breeding, irrigation, and application of available 4R
346 technologies have already made large gains, new technological developments may
347 be needed to achieve further gains, such as more affordable slow-release fertilizers,
348 nitrification and urease inhibitors, fertigation, and high-tech approaches to
349 precision agriculture⁵⁸. It is promising that the development and the combination of
350 information technology, remote sensing, and ground measurements will make the
351 information about precision farming more readily available, accessible, affordable,
352 and site-specific⁸². In many cases, large gains could still be made with more
353 widespread adoption of existing technologies, but a myriad of social and economic
354 factors affecting farmer decision making regarding nutrient management have only
355 recently begun to receive attention and are critical in improving NUE (ref. 15).
356 Socio-economic impediments, often related to cost and perceived risk, as well as
357 lack of trust in recommendations by agricultural extension agents, often discourage
358 farmers from adopting improved nutrient management practices^{59,60,83,84}.
359 Experience has shown that tailoring regulations, incentives, and outreach to local
360 conditions, administered and enforced by local entities, and where local trust and
361 “buy-in” has been obtained is essential for the success of efforts designed to improve
362 NUE (ref. 15).

363 While much of the work must be done at the farm scale, there are important
364 policies that should be implemented on national and multi-national scales. First,
365 improving NUE should be adopted as one of the Sustainable Development Goals

366 (SDGs)¹⁶ and should be used in conjunction with crop yield and perhaps other soil
367 health parameters to measure the sustainability of crop production systems. As
368 part of their commitments to achieve a SDG on NUE, countries should be strongly
369 encouraged to routinely collect data on their N management in crop and livestock
370 production. These data should be used to trace trajectories of the three indices of
371 agricultural N pollution, agricultural efficiency, and food security targets (i.e. N_{sur} ,
372 NUE, and N_{yield}), as we have done here (Fig. 5) to demonstrate where progress is
373 being made and where stronger local efforts are needed. The data used to construct
374 Fig. 5 have served to demonstrate trends, but both improved data quality and
375 international harmonization of data standards are needed. Regular attention should
376 be given to these trends to establish national and local targets and policies. Just as
377 protocols established by the Intergovernmental Panel on Climate Change permit
378 nations to gage their progress and commitment for reducing greenhouse gas
379 emissions, protocols for measuring and reporting on a SDG pertaining to NUE could
380 enable governments to assess their progress in achieving food security goals while
381 maintaining environmental quality.

382 Second, more attention is needed on nutrient management in livestock
383 operations and on human dietary choices. Here we have focused entirely on crop
384 production, largely because of availability of data, but the N_{sur} , NUE, and N_{yield}
385 indices are equally important in livestock management⁸⁵. Indeed, soybeans and
386 some cereals have high NUE as crops, but when fed to livestock, efficient recycling of
387 the manure-N is challenging, resulting in lower integrated NUE for the crop-
388 livestock production system⁸⁶. The crop production scenario used here for 2050

389 (Table 1) makes assumptions about future dietary choices³, which are beyond the
390 scope of this study, but we note that future trends in diet will affect the demand for
391 crop and livestock products, the crop mixes grown, and hence the NUE and N_{sur} of
392 future agricultural systems⁷².

393 Third, a similar approach to efficiency analysis would also be valuable for
394 phosphorus (P) fertilizer management, interactions of N and P management, and
395 reducing both N and P loading into aquatic ecosystems⁸⁷⁻⁹⁰.

396 Fourth, national and international communities should facilitate technology
397 transfer and promote agricultural innovation. Stronger international collaborations
398 and investments in research, extension, and human resources are urgently needed
399 for sharing knowledge and experience to create political and market environments
400 that help incentivize the development and implementation of more efficient
401 technologies. Technology transfer and capacity building will be needed to enable
402 Sub-Saharan African countries to tunnel through the EKC (Fig. 5).

403 These solutions to improving NUE will require cross-disciplinary and cross-
404 sectorial partnerships, such as: (1) integrating research and development of
405 innovative agricultural technology and management systems with socio-economic
406 research and outreach needed for such innovations to be socially and economically
407 viable and readily adopted by farmers; (2) analyzing the nexus of food, water,
408 nutrients, and energy management to avoid pollution swapping and to optimize the
409 net benefits to farmers, the environment, and society; (3) promoting knowledge and
410 data sharing among private and public sectors to advance science-based nutrient
411 management; and (4) training the next generation of interdisciplinary agronomic

412 and environmental scientists equipped with broad perspectives and skills
413 pertaining to food, water, energy, and environment issues.

414 The Environmental Kuznets Curve has often been described as an optimist's
415 view of a world with declining environmental degradation. Here we have shown
416 that there is evidence, indeed, hope for the EKC pattern of declining N pollution with
417 improving efficiencies in agriculture. However, we have also shown that
418 continuation of progress to date is neither inevitable nor sufficient to achieve
419 projected 2050 goals of both food security and environmental stewardship. Turning
420 points and trajectories of national agricultural EKC's will depend largely on
421 agricultural, economic, environmental, educational, and trade policies, and these
422 will largely dictate the food and pollution outputs of future agriculture.

423

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693

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708 **Author contributions**

709 X.Z., E.A.D., D.L.M., and T.D.S. designed the research. X.Z., T.D.S., and P.D. compiled
710 the N database. X.Z., Y.S., and E.A.D. carried out the statistical analysis. X.Z. and E.A.D.
711 led the writing of the paper with substantial input from D.L.M., T.D.S., P.D., and Y.S..

712 **Author Information**

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716 **Table**

717 Table 1. Nitrogen budget and Nitrogen Use Efficiency in crop production for different regions and major crop categories in
 718 2010 and projected for 2050. The 2010 record is aggregated from our N budget database (see Supplementary Information
 719 Section 1 for detailed methodologies and data sources used for developing this database). The 2050 projected Harvested-N is
 720 derived from a FAO projection of crop production to meet a scenario of global food demand³. The calculated target NUE values
 721 for 2050 are not meant to be prescriptive for particular countries or crops; rather, they are presented to illustrate the types of
 722 NUE values that would be needed, given this assumption of food demand³, while limiting N surplus near the lower bound (50
 723 Tg N yr⁻¹) of allowable N pollution estimated in planetary boundary calculations⁷⁸. Harvest-, input-, and surplus-N values are
 724 rounded to the nearest Tg N yr⁻¹.

	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
	<i>by region§</i>							
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
<i>by crop type¶</i>								
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

725 * The projected Harvest-N is based on an FAO scenario³ for 2050 that assumes 9.1 billion people and increases in average caloric consumption to 3200 kcal/capita in
726 Latin America, China, the Near East, and North Africa, and an increase to 2700 kcal/capita in Sub Saharan African and India. Consumption of animal products increases in
727 developing countries, but differences between regions remain.

728 § The definition of the country group is in Supplementary Table 13

729 ¶ The crop group is defined according to IFA's report on fertilizer use by crop³⁸

730 **Figures**

731 Figure 1. An illustration of the N budget in crop production and resulting N species released
732 to the environment. Inputs to agriculture are shown as blue arrows and harvest output as
733 a green arrow. Nitrogen use efficiency (NUE) is defined as the ratio of outputs (green) to
734 inputs (blue). The difference between inputs and outputs is defined as the N surplus, which
735 is shown here as red arrows for N losses to the environment and as N recycling within the
736 soil (orange box). Abbreviations include: biological nitrogen fixation (BNF), ammonia
737 (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), dinitrogen gas (N_2), ammonium (NH_4^+),
738 nitrate (NO_3^-), dissolved organic nitrogen (DON), and particulate organic nitrogen (PON).

739

740 Figure 2 An illustration of an idealized Environmental Kuznets Curve for (a) N surplus and
741 (b) the related curve for Nitrogen Use Efficiency. The theoretical limit for NUE (assuming
742 no soil mining of nutrients) is unknown, but no biological system is 100% efficient, so the
743 aspirational NUE limit is shown as close to but less than unity.

744

745 Figure 3. Examples of historical trends of the relationship between GDP per capita and N
746 surplus. The observations are the record of annual N surplus ($\text{kg ha}^{-1} \text{ yr}^{-1}$) for each country;
747 the model results are the outcome of the regression using the following model:

748 $Y = a + bX + cX^2$, where the dependent variable (Y) is the country's N_{sur} ($\text{kg ha}^{-1} \text{ yr}^{-1}$) and

749 the independent variable (X) is the country's GDP per capita. We categorized the 113

750 countries into 5 groups, based on the significance and sign of the regression coefficients “ b ”

751 and “ c ” (see Supplemental Information sections 2.1 and 3.1). In this figure, we present (a)

752 France and USA as examples of group 1, which have significantly positive “ c ”, thus
753 indicating that N_{sur} has started to level off or has declined; and (b) Brazil, Thailand, Malawi
754 and Algeria as the example of group 2 to 5, which increase non-linearly, increase linearly,
755 have no significant correlation, or have a negative surplus in 2007-2011, respectively (see
756 Supplementary Tables 5 and 6). The results for all countries can be found in the
757 Supplementary Figures.

758
759 Figure 4. A comparison of historical trends of (a) maize yield responses to N fertilizer input
760 (b) Nitrogen Use Efficiency (NUE) averaged across crops in China and the USA, and (c)
761 fertilizer to crop price ratios for China, India, USA, and France. The dashed blue line in
762 panel (a) shows a typical yield response function for maize based on fertilizer response
763 trials^{33,63}, which demonstrates diminishing return in yield as N inputs increase. Note that
764 the historical trend for China follows a similar pattern as a typical yield response function,
765 indicating that further increases in N application rates will result in diminishing yield
766 returns in China. In contrast, maize yield has increased in the USA since 2001 without
767 increasing nationally averaged N input rates, suggesting the yield improvement has been
768 achieved by adopting more efficient technologies or management practices that enable
769 shifting the yield response curve upwards³³. The dashed pink line in panel (b) shows what
770 the NUE in China would be if it achieved NUE values realized in the USA for all crops, but
771 with the crop mix in China. The gap between the dashed pink line and the black line (USA
772 record) is the difference between countries in NUE attributable to the differences in crop
773 mixes. The fertilizer to crop price ratio shown in panel (c) is determined by the nitrogen
774 price in urea divided by the nitrogen price in maize product (see Section 1.6 in

775 Supplementary Information for data sources and methodologies). The data are smoothed
776 using a ten-year window.

777

778 Figure 5. Historical trends of Yield-N, Nitrogen Use Efficiency, and N surplus, for a sample
779 of countries examined in this study. The grey scale shows the level of N surplus. The data
780 have been smoothed by ten years to limit the impact of year-to-year variation in weather
781 conditions. Curves moving towards the lower right indicate that those countries are
782 achieving yield increases by sacrificing NUE and increasing N surplus, whereas curves
783 moving towards the upper right indicate countries achieving yield increases by increasing
784 NUE and steady or decreasing N surplus.

785

Figure 1.

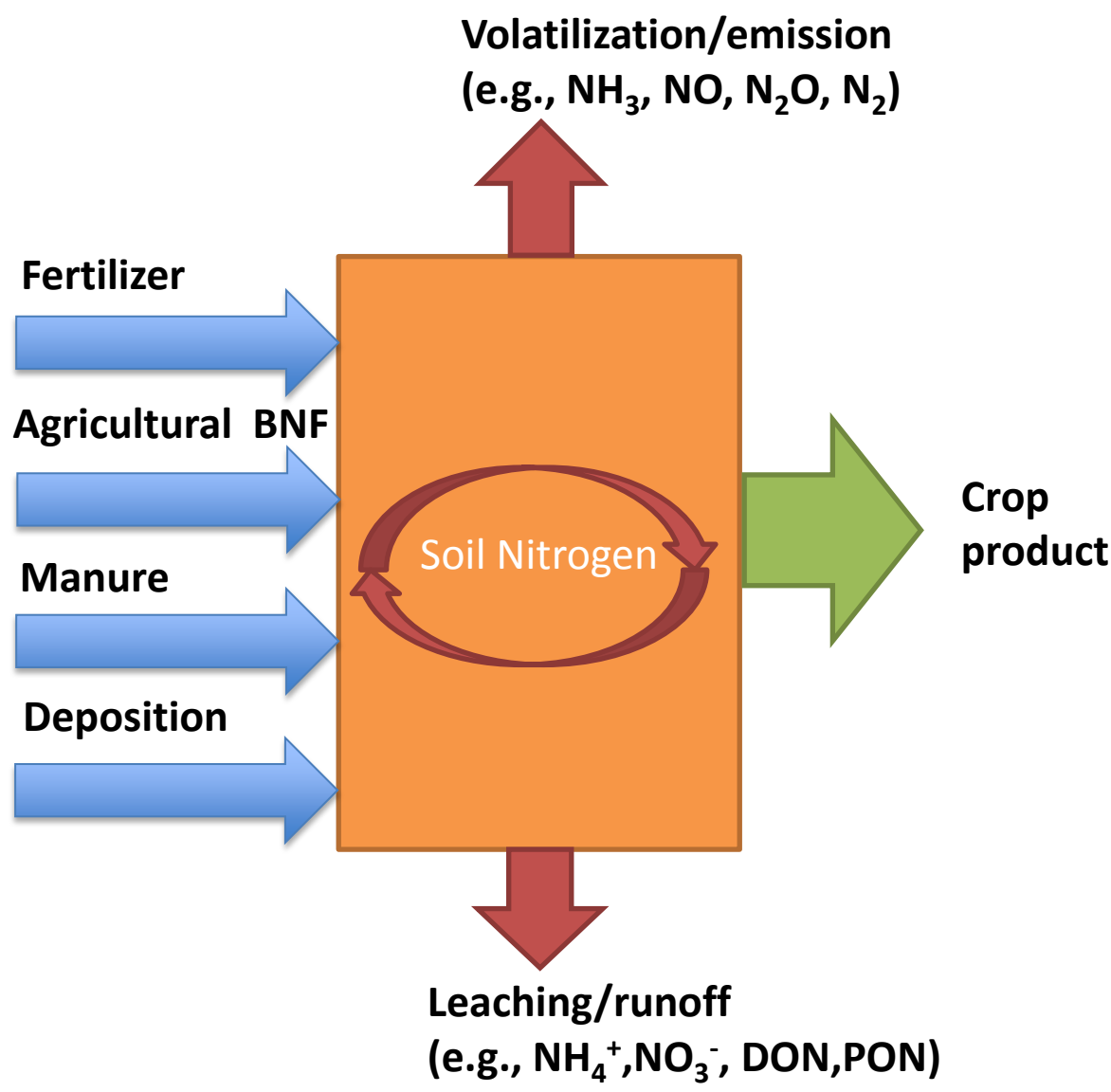


Figure 2.

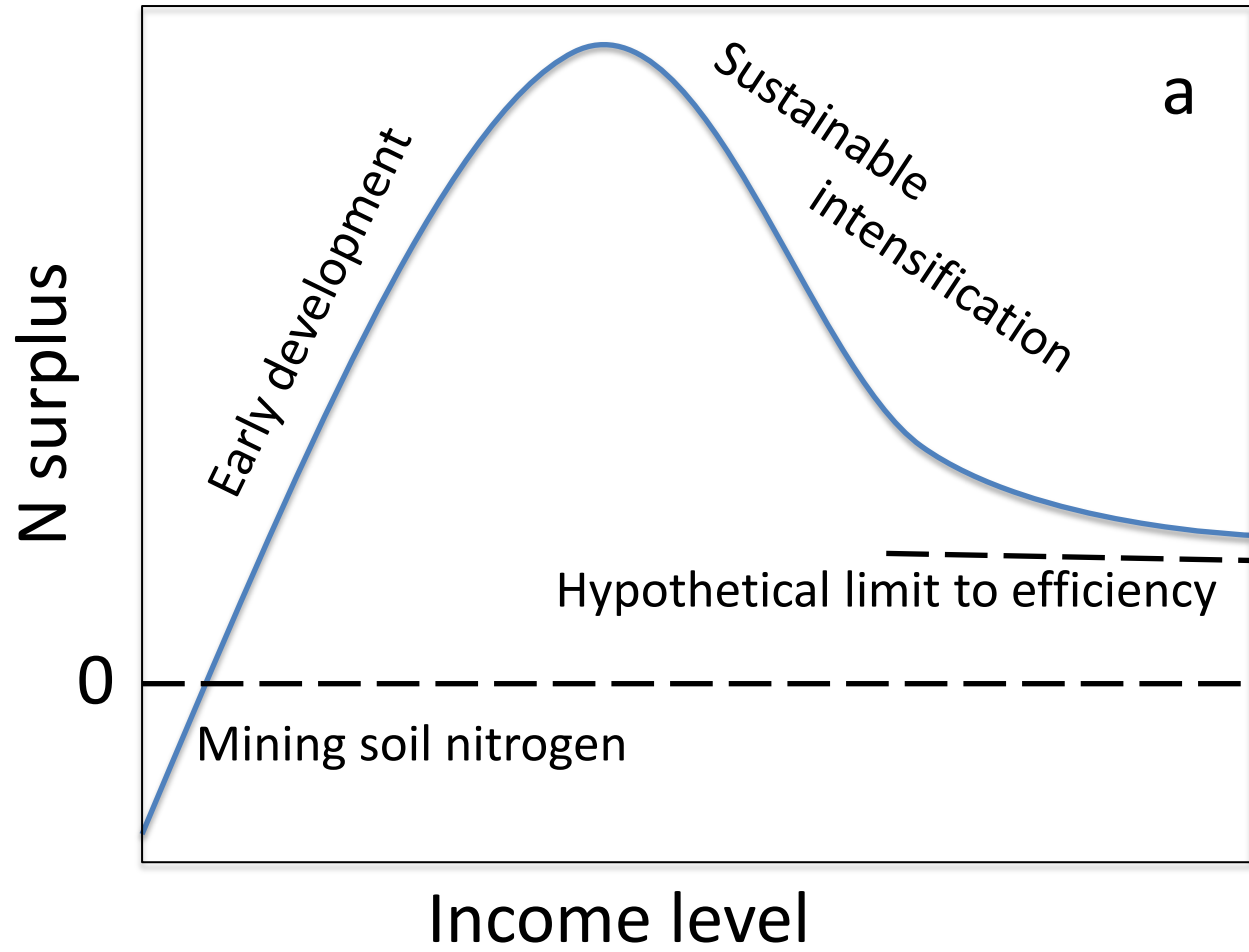


Figure 2.

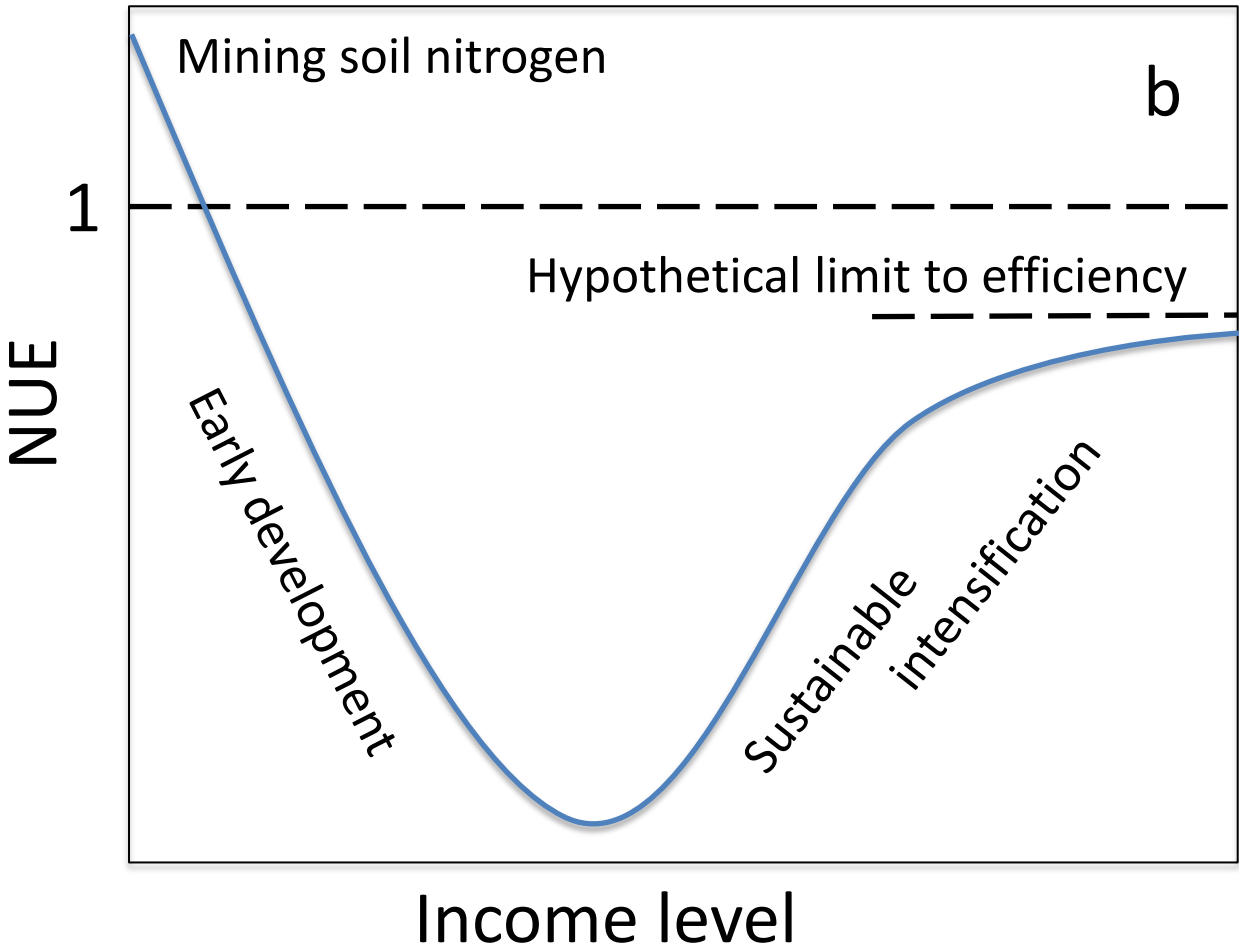


Figure 3.

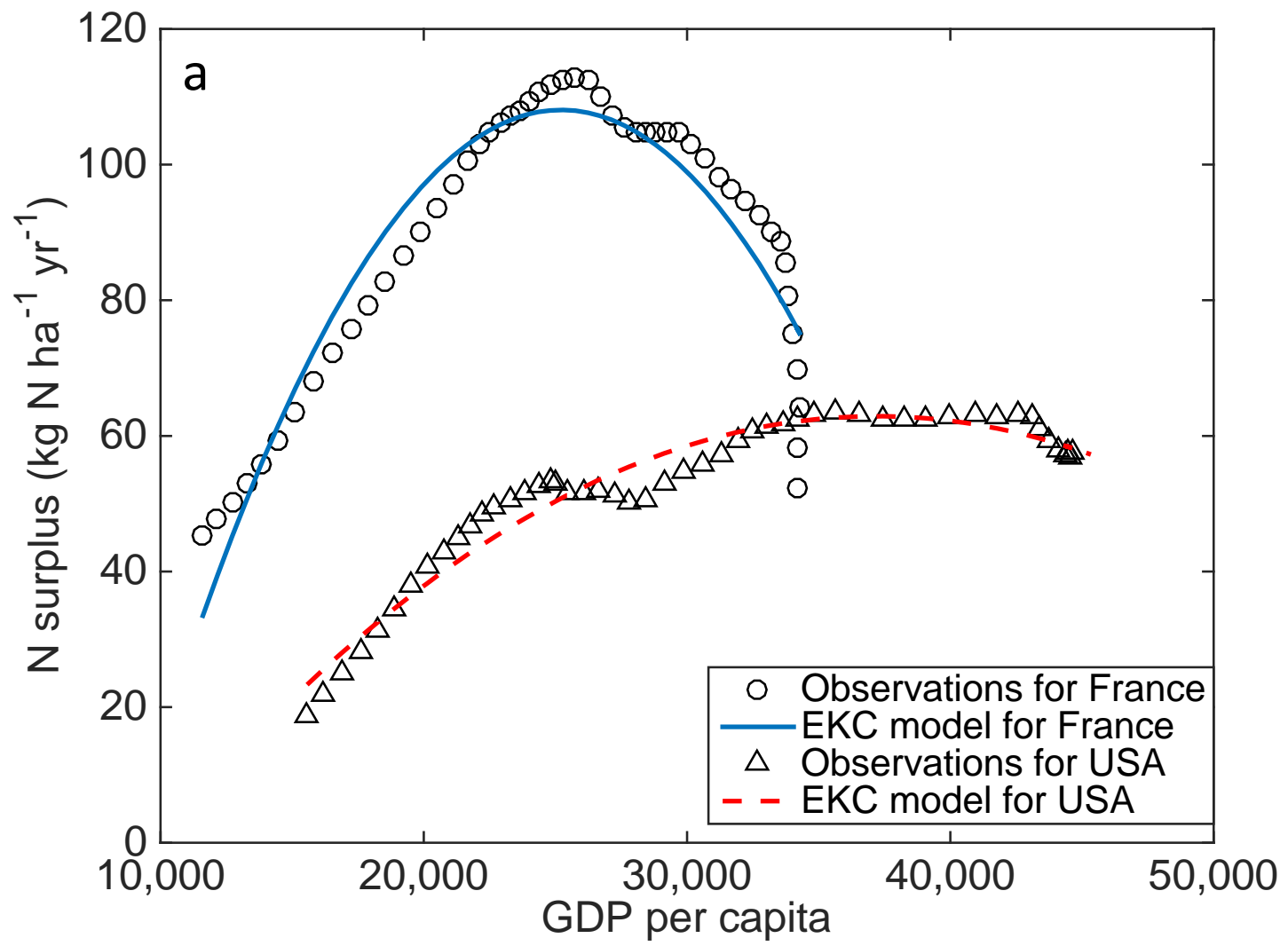


Figure 3.

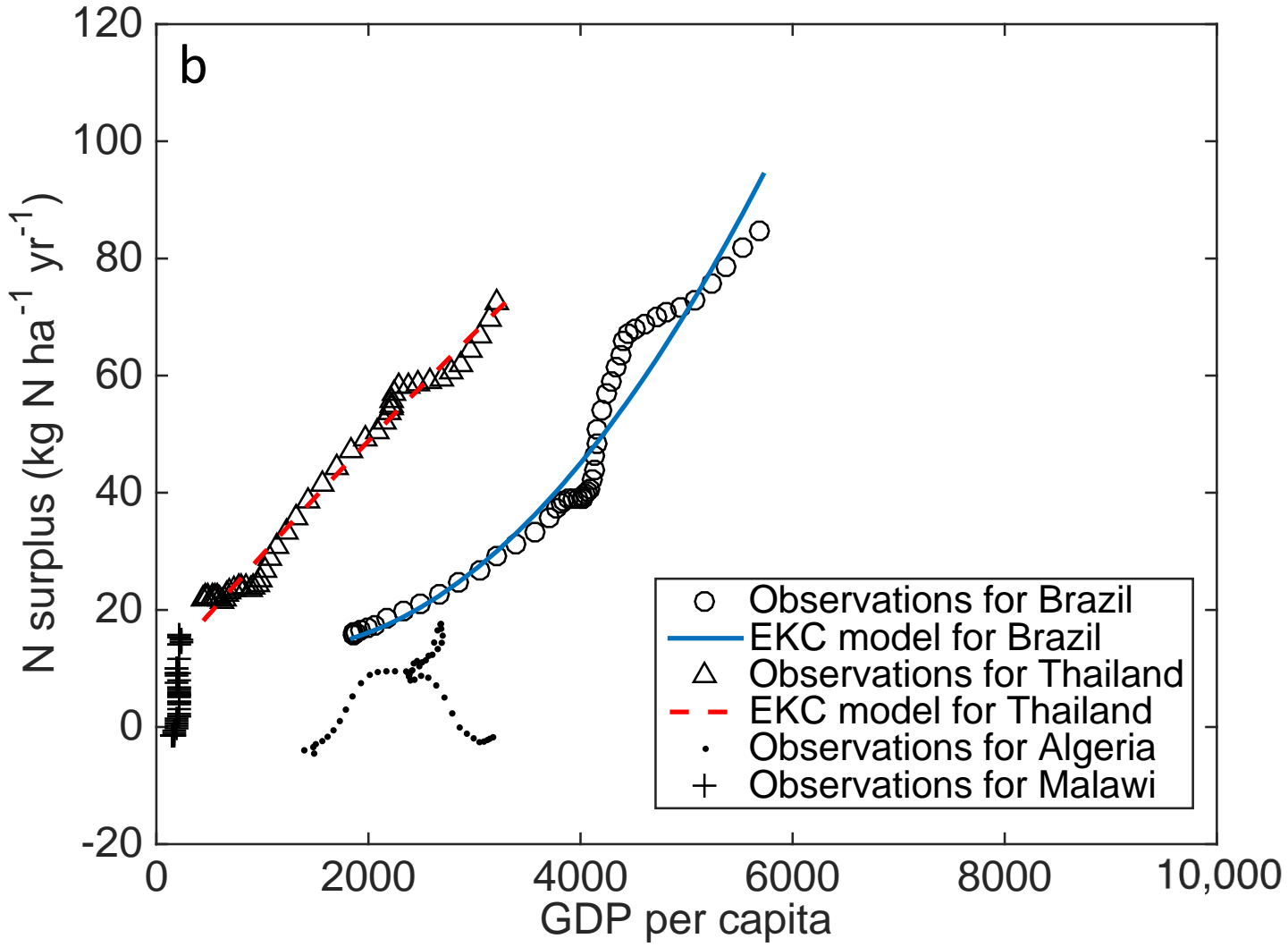


Figure 4.

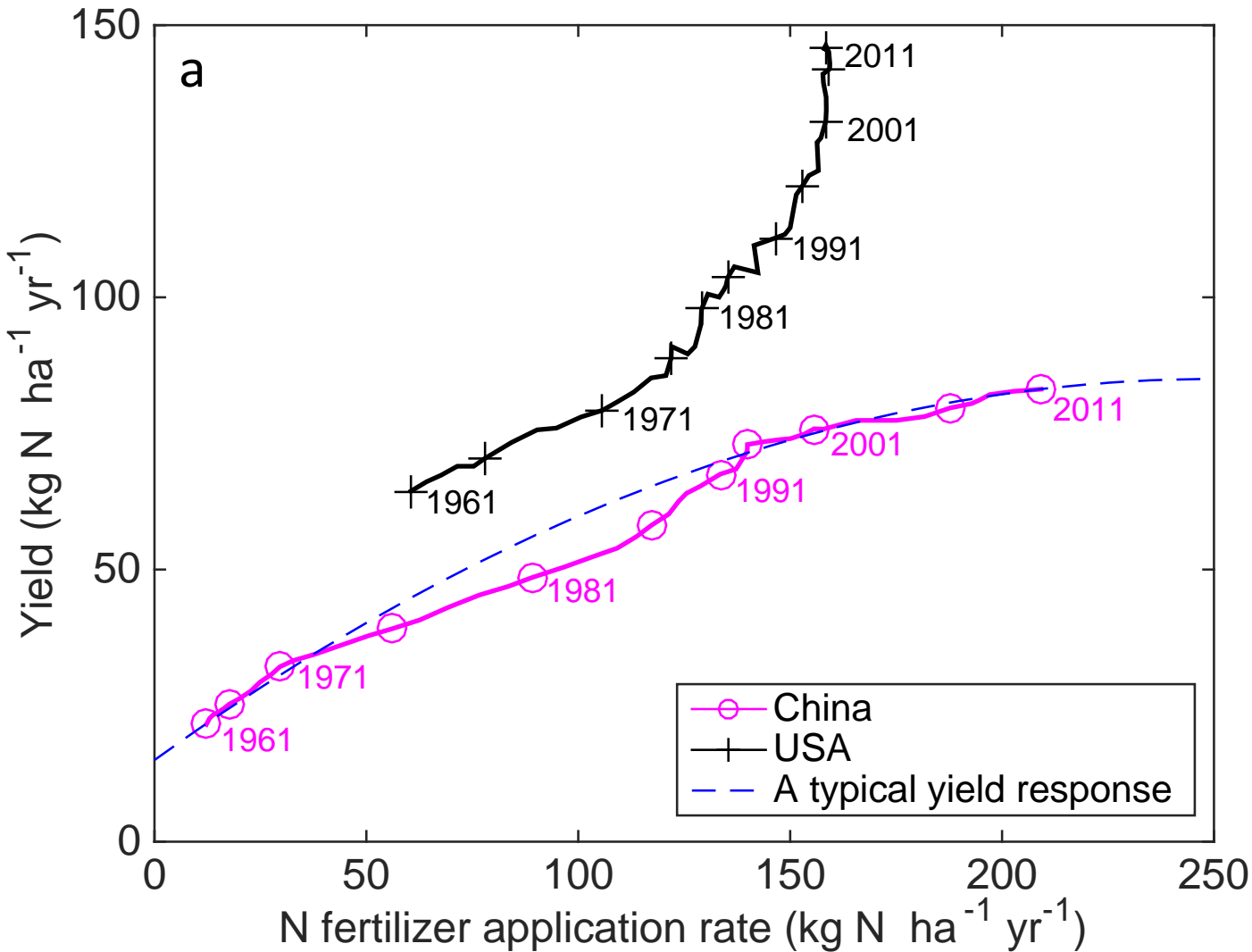


Figure 4.

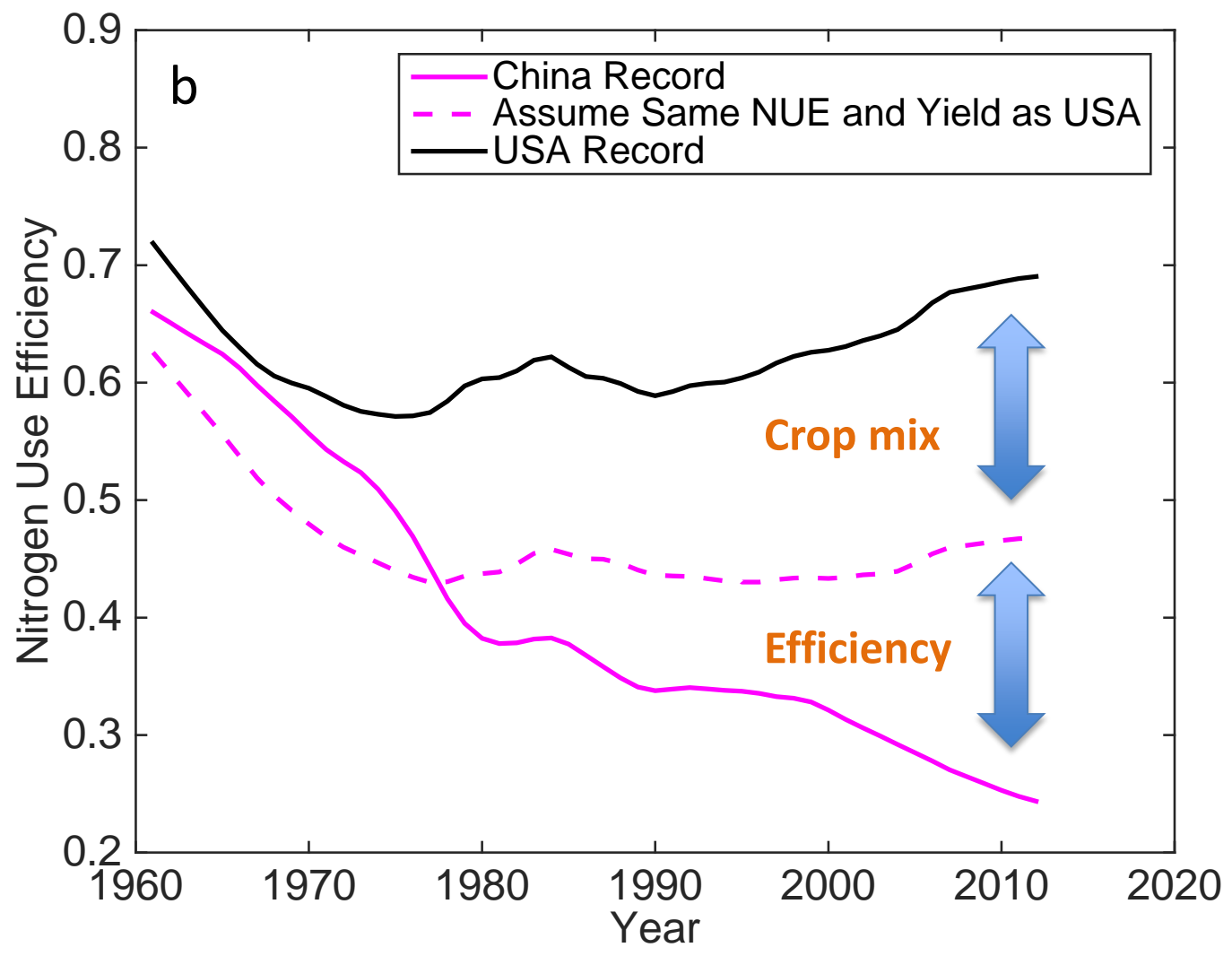


Figure 4.

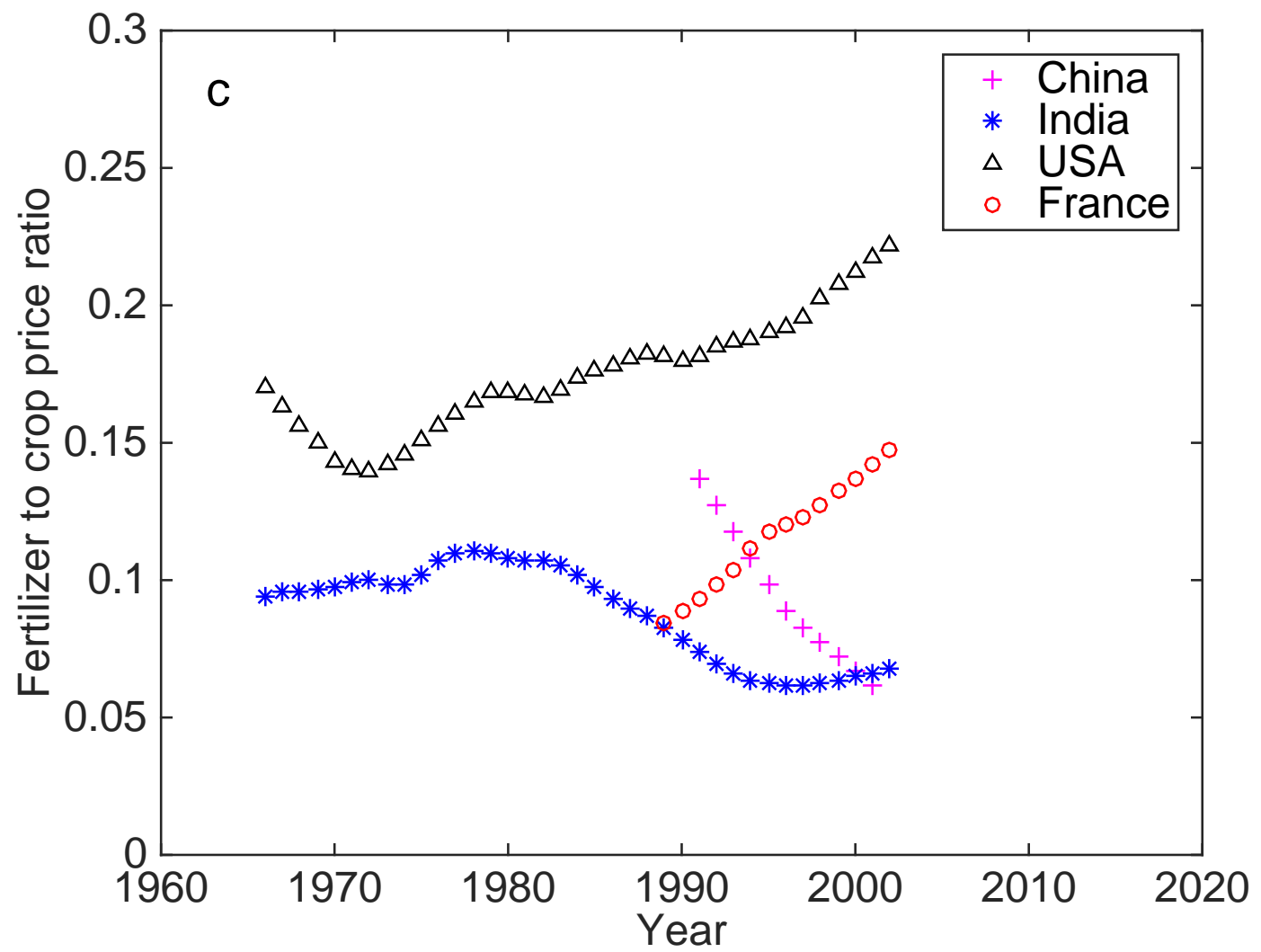


Figure 5.

