ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Projecting future nitrogen inputs: are we making the right assumptions?

IOP Publishing Environ. Res. Lett. 17 (2022) 054035 https://doi.org/10.1088/1748-9326/ac6619

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
19 November 2021

REVISED
18 March 2022

ACCEPTED FOR PUBLICATION
11 April 2022

PUBLISHED
4 May 2022

LETTER

Projecting future nitrogen inputs: are we making the right assumptions?

Srishti Vishwakarma[1], **Xin Zhang**[1,*] **and Nathaniel D Mueller**[2,3]

[1] Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, United States of America
[2] Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO, United States of America
[3] Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: xin.zhang@umces.edu

Keywords: nitrogen budget, nitrogen use efficiency, projection scenarios, technology and management practices, crop mix, yield response functions

Supplementary material for this article is available online

Abstract

Global use of reactive nitrogen (N) has increased over the past century to meet growing food and biofuel demand, while contributing to substantial environmental impacts. Addressing continued N management challenges requires anticipating pathways of future N use. Several studies in the scientific literature have projected future N inputs for crop production under a business-as-usual scenario. However, it remains unclear how using yield response functions to characterize a given level of technology and management practices (TMP) will alter the projections when using a consistent dataset. In this study, to project N inputs to 2050, we developed and tested three approaches, namely 'Same nitrogen use efficiency (NUE)', 'Same TMP', and 'Improving TMP'. We found the approach that considers diminishing returns in yield response functions ('Same TMP') resulted in 268 Tg N yr^{-1} of N inputs, which was 61 and 48 Tg N yr^{-1} higher than when keeping NUE at the current level with and without considering changes in crop mix, respectively. If TMP continue to evolve at the pace of past five decades, projected N inputs reduce to 204 Tg N yr^{-1}, a value that is still 59 Tg N yr^{-1} higher than the inputs in the baseline year 2006. Overall, our results suggest that assuming a constant NUE may be too optimistic in projecting N inputs, and the full range of projection assumptions need to be carefully explored when investigating future N budgets.

1. Introduction

Global nitrogen (N) inputs to crop production have increased from 37 Tg N yr^{-1} in 1961 to 163 Tg N yr^{-1} in 2009 contributing to a 69 Tg N yr^{-1} increase in crop yield [1]. While this change increased crop yields, it has led to adverse environmental impacts for climate, water quality, and air quality from regional to global scales [2, 3]. It has been proposed that global N inputs, mainly contributed by high- and mid-income countries, have already exceeded the so-called 'planetary boundary', which marks the safe operating space for humanity, by over 83%–142% [4]. In contrast, many regions of the world, such as sub-Saharan Africa (SSA), still have N inputs as one of the major limiting factors for crop yield [5–9]. To meet rising food demand, global crop production is projected to increase by 60%–110% by 2050 compared to 2005 baseline [10–13], suggesting a continuous increase in demand for N inputs worldwide. But the question of whether, where, and how much N inputs will continue to increase are critical for achieving future environmental sustainability and food security.

To project future N inputs and inform decision making related to N management, many studies have been conducted based on historical records of N inputs, nitrogen use efficiency (NUE; the fraction of applied nitrogen recovered in harvested crop), and food demand [12, 14–18]. Future N inputs can be calculated using projected food demand and NUE. The projection of food demand is usually based on the population and diet changes which have been described in shared socioeconomic pathways with a range of scenarios [19, 20]. Meanwhile, NUE is often considered as representative of technologies and management practices for N.

Many studies assume NUE to be staying constant, or even increasing, under a reference scenario or 'business-as-usual' (BAU) scenario, which considers that the state of technology and other socioeconomic conditions do not have major changes [14, 17, 21, 22]. However, considering the diminishing return of yield response to N inputs [23, 24], NUE will decrease if yield increases rely solely on rising N inputs without any improvements in technology and management practice (TMP). The concept of diminishing return of yield means stagnating crop yield with increasing N inputs, and it has often been utilized at farm-scale agronomic research [24–26].

Even though several recent studies implemented the dynamic yield response to N inputs in national or global scale analyses and N inputs projection (e.g. Lassaletta *et al* [1, 23]; Mogollon *et al* [18]; Mueller *et al* [27]; Billen *et al* [28–30]), most use aggregated N inputs or NUE of all crop classes and ignore the large variability in N inputs and NUE among crops and the impacts of changing crop mixes due to dietary shifts. At the global scale, NUE in 2010 varied from 0.14 to 0.80 among 11 major crop classes [31]. Such differences among crop classes are also evident on a national scale. For example, in China, average NUE (2011–2015) of different crops ranged from 0.08 to over 0.60 [32], while the aggregated NUE (i.e. NUE calculated for all crops) in China for year 2010 was 0.20–0.30 [1, 31]. Hence, using aggregated NUE instead of crop specific NUE will likely introduce bias to the projection of future N inputs.

Therefore, it is imperative to investigate how the assumptions made when constructing N projections affect findings about the future of N inputs. As there is considerable variability among global N budget datasets [33], as well as datasets from different spatial scales [34], it is also critical to utilize a consistent dataset in a simple and transparent manner to reveal the importance of NUE and technology scenarios. Consequently, we update and use a database of N budgets by country and crop class for 115 countries or regions during 1961–2015; design and implement three approaches to project N inputs in 2050 considering different assumptions for NUE and yield response; compare our projections with existing literature; and discuss the implications of our findings for future N projections.

2. Material and methods

2.1. Data

This study used the Global Database of Nitrogen Budget in Crop Production, a country- and crop- specific N budget database, and updated it for the period of 1961–2015 based on the methodologies developed by Zhang *et al* [31]. The total N inputs to cropland included N-fertilization, N-manure, N-fixation and N-deposition in kg N ha^{-1} yr^{-1}, while the output included crop yield (i.e. grains or editable parts of the crop only; straw and residues are not included) representing N in harvested crop (kg N ha^{-1} yr^{-1}). The N-manure represents the amount of manure collected and applied to cropland. The analysis was performed with a focus on the crop production system, and was carried out for 115 countries or regions based on the list of major crop producing countries used in Zhang *et al* [33] for statistical assessment, and 11 crop classes following International Fertilizer Association's (IFA) guidelines [35] (see SI tables S1 and S2 available online at stacks.iop.org/ERL/17/054035/mmedia). Projections of crop yield and harvested area for year 2050 were from Food and Agricultural Organization of the United Nations (FAO) 2012 report [20] with baseline year of 2006 (averaged 2005–2007), which was derived based on food demands and is in line with historical trajectories of N yield for major regions (figure S17). The projected crop yield is expressed in kg N ha^{-1} yr^{-1}.

2.2. Assumptions and approaches for projection

To project N inputs in 2050, we designed three approaches using the same projected crop demand but different assumptions for NUE (table 1 and SI text S3).

2.2.1. 'Same NUE' approach

The first approach, named 'Same NUE', assumes that NUE stays the same as the current level (i.e. averaged NUE for 2011–2015). We first estimated the NUE for each country (k) and crop class (c) for the 2011–2015 period (t), then calculated N input rates in 2050 using projected crop yields in 2050 [20] divided by the estimated NUE assuming that NUE stays the same in 2050 (SI equation (1)). We then calculate total N input quantity in 2050 using the harvested area from the same report [20] (SI equation (2)). In order to investigate the impacts of changes in crop mixes on the projection of N inputs, we also tested the projection with the aggregated NUE of all 11 crop classes in a country instead of the crop-specific NUE (see SI text 3.1 for details).

2.2.2. 'Same TMP' approach

The second approach, 'Same TMP,' considers the TMP (represented by the yield response function derived from the observations during 2006–2015) stay the same as the current level. Under the same TMP and ecological conditions, yield response to N inputs levels off as N inputs increases, and consequently NUE decreases. Yield response functions have been developed to characterize such relationship between N inputs and yield [23, 36–38]. The yield response function could be changed due to the adoption of new TMP, such as precision farming, controlled release fertilizer, nitrification inhibitors and polymer-coated fertilizer [24].

Table 1. Summary of projection approaches and their assumptions.

Projection approaches	Assumptions
Same NUE	NUE for each country stay the same at current level (i.e. averaged NUE for 2011–2015)[a]
Same TMP	The yield response function, representing the level of TMP as well as environmental conditions, stays the same as the current level (i.e. determined by observations from 2006 to 2015)
Improving TMP	The yield response function keeps evolving following the pace and trajectory observed in the past decades (1961–2015)

[a] This approach was tested in two cases: one considers the changes in crop mixes and the other does not.

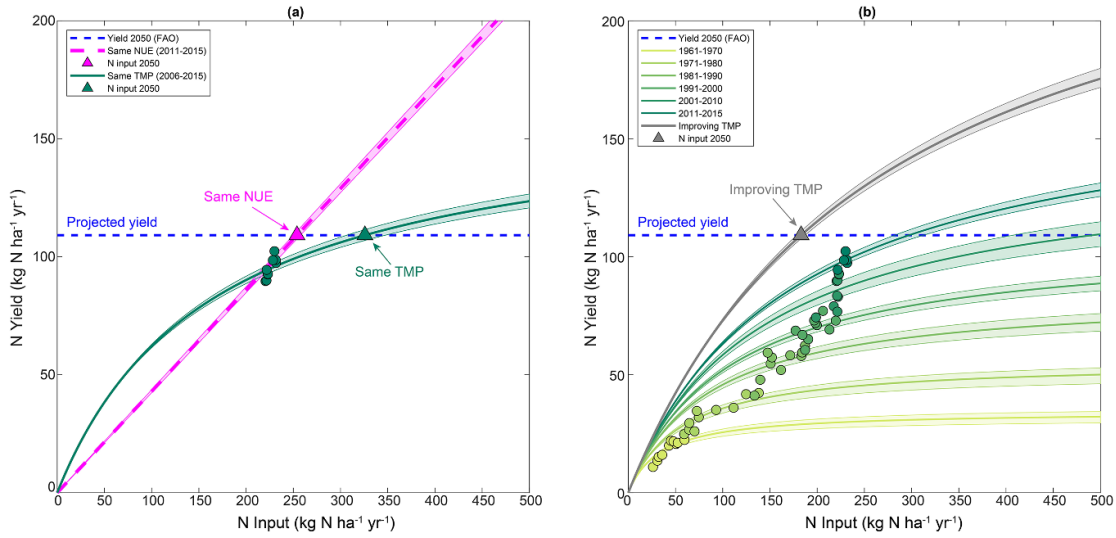

Figure 1. Illustration of projection approaches using N use data for China's wheat production as an example. The projected N inputs are shown as colored triangles: pink and green triangles for 'Same NUE' and 'Same TMP' approaches (panel a) and grey triangles for 'Improving TMP' approach (panel b). The pink dashed line represents average NUE for 2011–2015 (panel a). The yield response relationships estimated using one-parameter hyperbolic relationships are represented as colored lines: Green and grey lines for 'Same TMP' (2006–2015) (panel a; SI equation (5)) and 'Improving TMP' scenario (SI equations (5) and (7)), respectively, while other green lines in panel b are yield response relationships for different period from 1961–2015 (panel b; SI equation (5)). The shaded area around lines is the 95% confidence interval estimated using 1000× bootstrap resampling. The blue horizontal line is the 2050 yield target obtained from FAO 2012 report.

Based on the N inputs and yield records for the most recent ten years (i.e. $t =$ 2006–2015), we first estimated a yield response function for each country and crop class (SI equation (5); figure 1(a)). Then, we used these yield response functions to estimate N input rates when yield changes to 2050 level (SI equation (6)). Similar to several published studies [18, 23, 27], we adopted one-parameter hyperbolic function as yield response function; meanwhile, we also carried out uncertainty test to investigate the impact of using different function forms (e.g. quadratic plateau function) on projection results.

2.2.3. 'Improving TMP' approach

The third approach 'Improving TMP,' assumes that TMP keeps evolving following the pace and trajectory observed in the past decades (1961–2015). Therefore, for each country and crop class, we first estimated yield response functions based on the N inputs and yield records for each of the six time periods between 1961 and 2015 (figure 1(b)). As the coefficient of the hyperbolic yield response function ($M_{k,c,t}$) represents maximum achievable yield, it serves as an indicator of the TMP level represented by the yield response function [23]. Larger values of the coefficient demonstrate improvement in TMP, and vice-versa [18]. Consequently, we used $M_{k,c,t}$ for the past six time periods to extrapolate to 2050 and estimate a new yield response curve, which is then used to estimate N input in 2050.

2.3. Uncertainty tests

We examined three potential sources of uncertainties for projected N inputs: (a) the uncertainty associated with estimated parameters in the yield response function, (b) the effect of using different yield response functions, and (c) the effect of yield response to non-fertilizer N inputs (see text S6 for details).

3. Results

3.1. Projection of global N inputs

While all approaches projected significant increase in global N inputs by 2050, the range of projected

Table 2. Global N inputs (Tg N yr^{-1}) for 2050 with different approaches and their variants.

Approaches	Variants	N inputs (Tg N yr^{-1})	NUE	N surplus
Baseline	Baseline year 2006	145	0.45	80
Same NUE	With crop mixes	207 [200-215]	0.49 [0.47-0.50]	107 [100-115]
	Without crop mixes	220 [213-226]	0.46 [0.44-0.47]	119 [113-126]
Same TMP	One-parameter hyperbolic yield response function	268 [254-295]	0.38 [0.34-0.40]	168 [153-194]
Improving TMP	One-parameter hyperbolic yield response function	204 [196-229]	0.49 [0.44-0.51]	103 [95-128]

Note. Using bootstrap resampling for 1000×; the values within brackets are 95% confidence intervals.

increase varies substantially, from 41% to 85% relative to the baseline year 2006 (average 2005–2007) (table 2). The 'Same TMP' approach projects that global N inputs will reach 268 (254–295; 95% confidence interval) Tg N yr^{-1} by 2050, significantly higher than the 'Same NUE' approach, which projects 207 (200–215) Tg N yr^{-1}. The higher projected N inputs are accompanied with lower NUE and higher N surplus by the 'Same TMP' approach than those projected by the 'Same NUE' approach (table 2). This demonstrates that future N input could have been underestimated by ignoring the diminishing return in yield response to N inputs. On the other hand, the projected N input by the 'Improving TMP' approach, 204 (196–229) Tg N yr^{-1}, is not significantly different from the 'Same NUE' approach. No significant difference between the two methods is found in projected NUE and N surplus either. It suggests that N inputs could be maintained around the level projected with 'Same NUE' if TMP keeps improving at the pace of past five decades, which could be a very optimistic assumption.

Projecting N inputs without considering the shifts in crop mix leads to biases in the projection. Taking the 'Same NUE' approach as an example, using the aggregated NUE for all crops instead of crop specific NUE results in an overestimation of 13 Tg N yr^{-1} (or 6%) for future N inputs globally (table 2), and such overestimation is larger in regions with strong shifts towards N efficient crops (e.g. soybean). However, this difference is lower than the difference between the 'Same NUE' and the 'Same TMP' approaches.

The projected N inputs are not significantly affected by the potential different yield response to fertilizer and non-fertilizer inputs (SI text S6.3 and table S5). When N-fixation is assumed to be constant and stay at the current level until 2050, the projections are around 7 Tg N yr^{-1} (or 3%) lower than the N inputs projected from the 'Same TMP' approach that uses all N inputs in the yield response curve. In contrast, when only N-fixation followed the yield response curve and the remaining N-inputs are assumed to stay at the current level until 2050, the projections are 36 Tg N yr^{-1} (or 13%) lower than the 'Same TMP' approach.

3.2. Regional N input differences

Most countries around the world project increase in N inputs from baseline year to 2050 across all approaches used in this study (figure 2). India and Brazil may increase N inputs by 14–26 (the lower and upper bounds of projection results from different approaches) and 8–12 Tg N yr^{-1} respectively, the top two countries with the largest increase in all tested approaches. But these additional N inputs will be utilized at a very different NUE level, namely 0.23–0.30 in India and 0.45–0.57 in Brazil (figure S7). The USA, China, and Argentina are among the top five countries considering the projection with the 'Same TMP' or 'Same NUE' approach only; but N input may reduce from the baseline level in China following the 'Improving TMP' projection. Despite the projection methods, the NUE in China and India are consistently lower than USA, Argentina and Brazil (figure S7), suggesting the critical role of improving NUE for reducing global N inputs and the urgency of accelerating the development and adoption of nitrogen-efficient agricultural practices (i.e. improved TMP) in these two countries. We further note the critical situation in India, where NUE is projected to decline even in the 'Improving TMP' approach, suggesting the pace of TMP improvement in the past decades is not even sufficient to keep the NUE constant.

Among the nine world regions [39], Asia accounts for the largest fraction of global N input for the baseline year (about 52%) and is also the region projected to experience the largest increase in N inputs regardless of the projection methodology (figure 3). About 57% of the increase is contributed by India. In comparison, SSA accounts for 3% of global N input for the baseline year, but its projected increase is 8–22 Tg N yr^{-1}, about 174%–502% of the current level. SSA has the largest variation in projected NUEs among all world regions, suggesting how TMP will be adopted in SSA is critical in determining the future N inputs in this region [40] (figure S8).

Almost all countries and regions project the largest increase in N inputs with the 'Same TMP' approach, higher than both 'Same NUE' and 'Improving TMP' approaches. This observation confirms that ignoring the diminishing return in yield

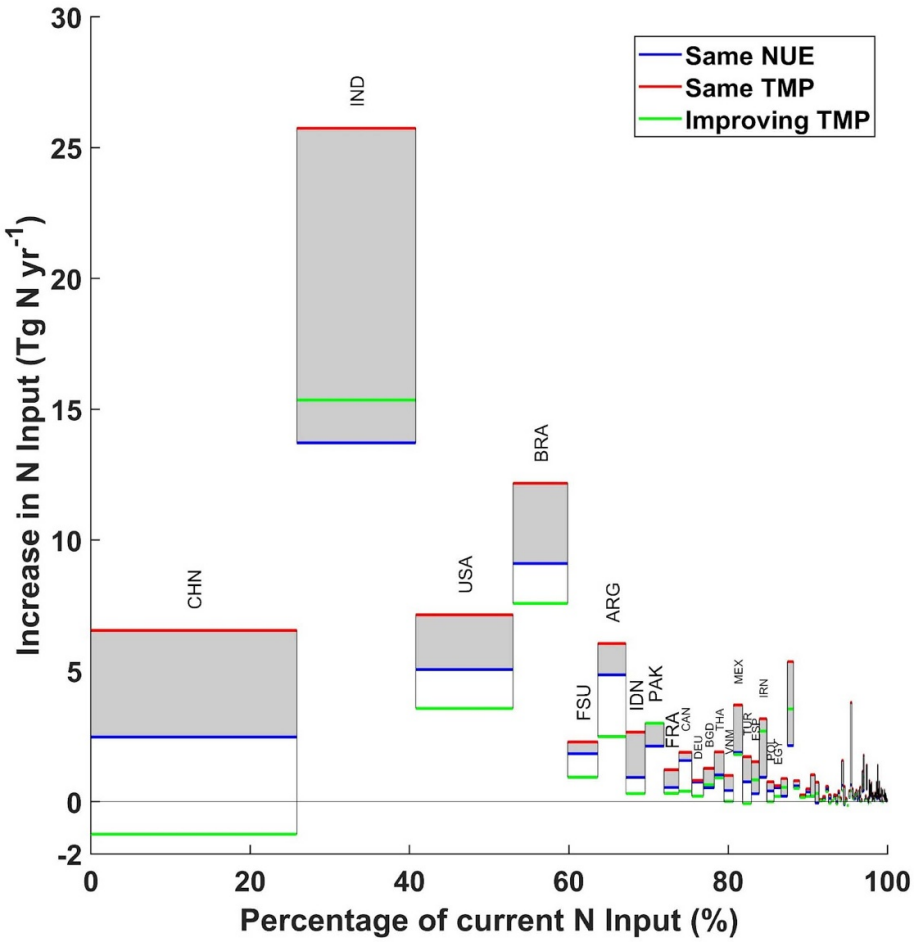

Figure 2. Projected country-level increase (decrease) in N inputs in 2050 relative to baseline year 2006 (average 2005–2007). Each box represents a country. Each country is represented by the three-letter acronym following the definition of ISO alpha-3 country code (ISO 3166–1: 2013). The horizontal lines in the box show the changes in projected N inputs from baseline, while the width of the line shows the country's N input contribution in the baseline year. The filled grey box shows the distinctness between 'Same NUE' and 'Improving TMP' approaches. The countries are arranged in a decreasing order of their N inputs in the baseline year. Key crop producing and trading countries like China, India, USA, Brazil, Former Soviet Union (FSU), Argentina, and Indonesia are among top contributors in the global N input of 100 Tg N yr^{-1} out of 145 Tg N yr^{-1} in the baseline year.

response (i.e. the 'Same NUE' approach) may underestimates future N inputs on a national scale. Almost half of countries (about 43%, e.g. China and USA) show higher projection with 'Same NUE' than with 'Improving TMP' approach. It indicates that these countries may improve NUE while reaching the target yield, if the TMP keep the pace of improvement as the past five decades. But there are countries (e.g. India and Pakistan) show the opposite pattern, indicating the improvement in TMP need to be accelerated in order to increase NUE and achieve the target yield.

3.3. Crop specific N input differences

Across all the approaches used for projection, N inputs for each of the 11 crop groups are projected to increase. However, the level of projected increase varies largely, attributing not only to the different increases in production levels but also to the different projection approaches (figure 4). For example, with the 'Same NUE' approach, soybean is projected to increase N inputs by 13 Tg N yr^{-1}, the highest among all crop groups, and it is mainly contributed by 80% expansion in production level globally. In contrast, with the 'Same TMP' approach, maize projects the highest increase in N inputs at the level of 26 Tg N yr^{-1}, about 98% higher than the projection by the 'Same NUE' approach. In contrast to the large variation in projected N inputs, the differences in NUE caused by projection approaches are smaller than the differences among crop classes (figure S9): across all projection approaches, soybean has the highest NUE at 0.73–0.81 (the lower and upper bounds of projection results from different approaches) in 2050; the NUEs for rice, wheat and maize range from 0.35 to 0.53; and fruits and vegetables and sugar crops showed the lowest NUEs at 0.14–0.20.

The projected increase by the 'Same TMP' approach is consistently higher than the other two approaches indicating the impact of diminishing return in yield to N inputs in projection. Meanwhile, the 'Improving TMP' approach projects the lowest

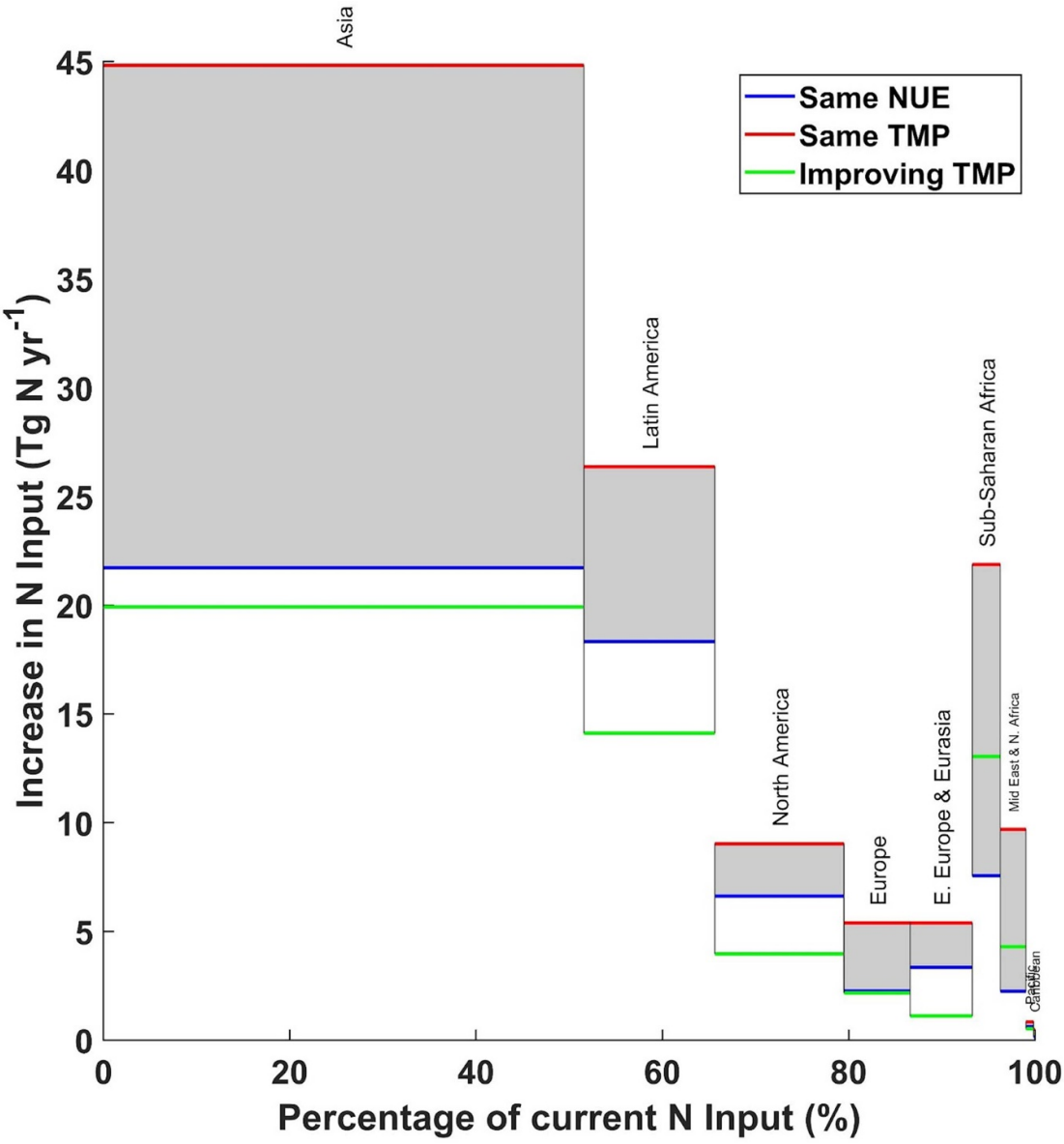

Figure 3. Projected regional-level increase (decrease) in N inputs from baseline year 2006 (average 2005–2007). Each box represents a region. The horizontal lines in the box show the changes in projected N inputs from baseline, while the width of the line shows the region's N input contribution in the baseline year. The filled grey box shows the distinctness between 'Same NUE' and 'Improving TMP' approaches. The regions are arranged in a decreasing order of their N inputs in the baseline year.

increase in N inputs for most crop classes except fruits and vegetables, other crops and sugar crops. It suggests that, for these three crop classes, improving TMP at the pace of past five decades will not be sufficient to maintain NUE with the intensifying production. Considering their current NUEs are already the lowest among all crop classes, this result highlights the urgency for accelerating the improvement in N management for these crops.

4. Discussion

4.1. Are we being optimistic to assume constant NUE with increased crop production?

The much higher projected N inputs from the 'Same TMP' than the 'Same NUE' approach suggest that we have been optimistic about the future NUE by assuming it stays the same as we increase the crop production under the BAU scenario. On a farm scale, it has been widely recognized that the yield response to N inputs gradually levels off as N inputs and yield increase for a given farm and TMP level [24]. Applying this theory of diminishing return to a broader spatial scale [23, 27] suggests that achieving the higher production level (i.e. higher yield) without expansion in cropland area and TMP improvement results in decline in NUE. Besides increasing yield on the existing cropland, crop production could be increased by expanding the existing cropland at the expense of other land including natural habitat; however, when the expansion is on marginal land, it is unlikely to achieve the same NUE and yield as the current level.

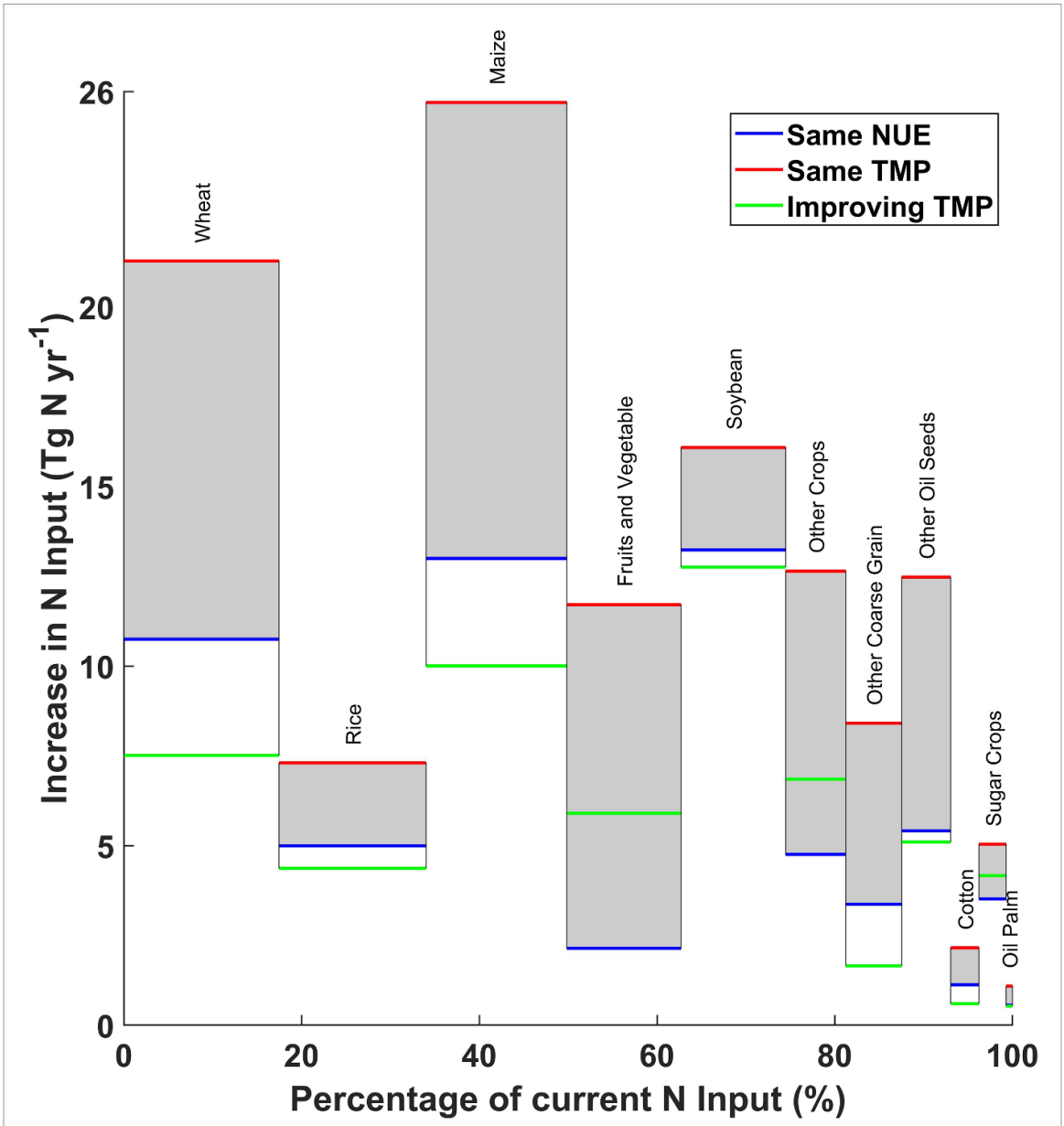

Figure 4. Projected crop-level increase (decrease) in N inputs from baseline year 2006 (averaged 2005–2007). Each box represents a crop class. The horizontal lines in the box show the changes in projected N inputs from baseline, while the width of the line shows the crop's N input contribution in the baseline year. The filled grey box shows the distinctness between 'Same NUE' and 'Improving TMP' approaches. The crop classes are arranged in a decreasing order of their N inputs in the baseline year.

The shifts in crop mix towards more N-efficient crops (e.g. soybean) reduce total N inputs, but the reduction is relatively small when comparing to the difference in N inputs caused by different TMP assumptions. Based on the crop production portfolio projected by FAO [20], soybean production (with world average NUE of 0.80; Zhang *et al* [31]) will increase by 80%, requiring less N inputs per unit of crop product than other crops. But the NUE increases due to the expanding soybean is compromised by the continuous expansion of fruits and vegetables production (with world average NUE at 0.14; Zhang *et al* [31]), which is projected to increase more than 80% [41]. In addition, the current increase in soybean production is mostly used for animal feed, only a small fraction of which will be converted to food products [42], therefore, it is important to recognize that improving NUE for the whole food supply chain is critical in addition to improving the NUE for crop production [2, 43, 44].

4.2. Uncertainties in the projection

Three major sources of uncertainties were examined in this study. The first uncertainty was associated with the parameters in the yield response function, and was quantified and reported along with the main result. The second uncertainty was associated with the choice of the yield response function format, and was evaluated by testing additional function forms. The use of quadratic plateau function resulted in higher N inputs projection than hyperbolic yield response function (see SI table S4). It leads to even larger

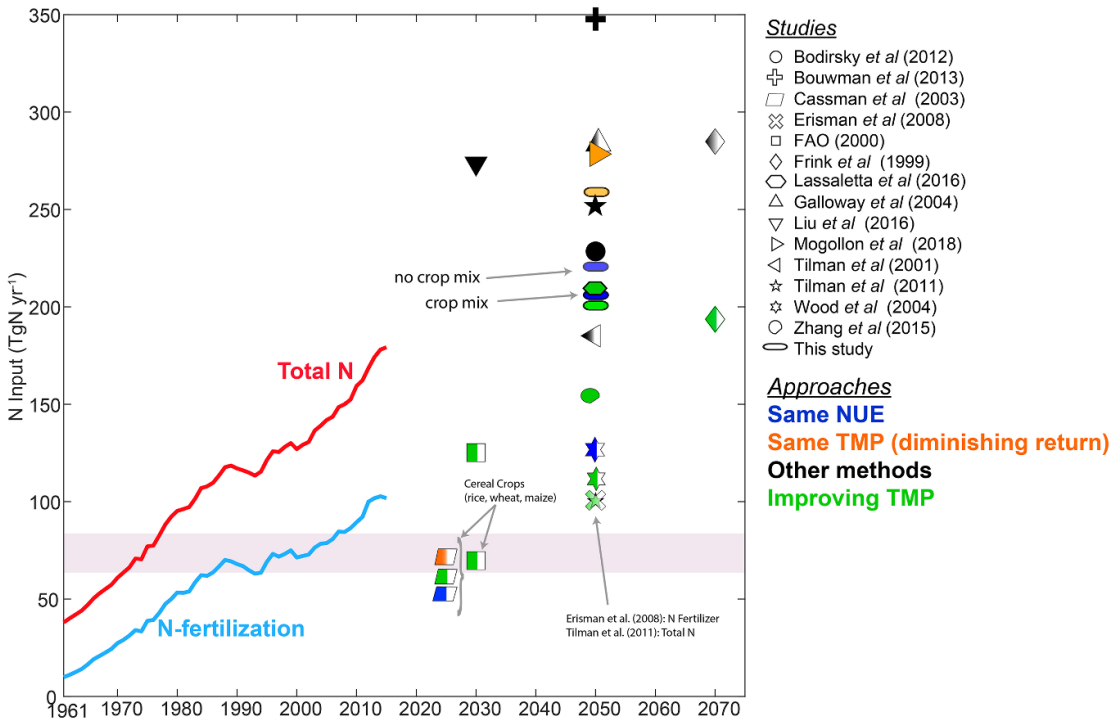

Figure 5. Projections of N input from different studies along with the projection estimates from this study. Each symbol shows different studies, while their fill color shows the estimates corresponding to the approaches. If a symbol is filled entirely (half-filled), then the projections are for total N (N fertilizer), respectively. Projections only for cereal crops are indicated by arrows, while estimates which include all crop classes are not. The horizontal pink stripe demonstrate the planetary boundary (62–82 Tg N yr^{-1}) of anthropogenic N inputs from fertilizer and biological N fixation introduced into the earth system adopted from Steffen *et al* [4]. The red and blue line show historical records of total N and N fertilization from 1961 to 2015, respectively. The details of the projections from these studies are in SI table S6.

difference between the 'Same TMP' and 'Same NUE' approaches, supporting our conclusions regarding the impacts of considering diminishing returns on N input projection. Indeed, yield increases are not only limited by N inputs and N management, but also affected by factors such as the availability of other macronutrients (e.g. phosphorus), micronutrients, and water. Although our approaches do not explicitly express these factors as parameters in the yield response function, they are implicitly reflected in our yield response functions since changes in these factors can shift the yield response curves (i.e. changes in TMP). The third uncertainty was about the potential difference in yield response to fertilizer and non-fertilizer inputs and was assessed by varying the use of fertilizer and non-fertilizer inputs in the yield response function. However, no significant differences were found in the global as well as the crop specific projections (SI table S5).

A survey of existing projections for crop N inputs reveals large variations among studies (figure 5), which could be attributed to a range of causes, such as projection methods and assumptions, the coverage of N inputs (total N vs fertilizer only), the baseline year, the projection year, and the coverage of crop classes considered (See SI table S6). Among all studies, Mogollón *et al* [18] and Lassaletta *et al* [1] are the only two studies to consider the diminishing return in yield response. Their projection approaches correspond to 'Same TMP' and 'Improving TMP' approaches in this study respectively, and the projection results are about 12 Tg N yr^{-1} and 3 Tg N yr^{-1} higher than our results, respectively. The differences are mainly caused by their approach to project yield response function (M) to 2050. The Mogollón *et al* [18] projected M based on the relationship between M and gross domestic product for each world region in their study, whereas we performed linear extrapolation of M to project future yield response curve and N inputs. In contrast, Lassaletta *et al* [1] used the past three decades (1980–2009) for extrapolation of yield response curve, while we used the past five decades (1961–2015). Additionally, they projected N inputs by considering aggregated crop production of 12 regions of the world, while we projected it for each country and crop mixes combination. Other studies within the 'Improving TMP' approach, such as Wood *et al* [22] and Erisman *et al* [14], assume an increase in NUE by 30% and 50% by 2050 relative to the baseline (1997 and 1995–97) resulting in 107 and 100 Tg N yr^{-1} N fertilizer inputs for cropland, respectively. Despite using different approaches, their projections estimates are similar to our N fertilizer projection in the 'Same NUE' approach which is around 114 Tg N yr^{-1} (assuming fraction of fertilizer in total N stay the same as in baseline year). Cassman

et al [21]and Wood *et al* [22] assumed constant NUE in their projection, but Cassman *et al* [21] was projecting for an earlier year 2025. Accounting for N fertilizer inputs only, our projection in the 'Same TMP' approach is about 15% higher than Cassman *et al* [21] and 6% lower than Wood *et al* [22]. Despite the difference, almost all projections are outside the N planetary boundaries [4, 45], and most of the predictions are surpassing the upper bound of the uncertainty range for the planetary boundaries. Overall, this study presents projections comparable to values in literature, and it is among the first to systematically evaluate the impacts of yield responses under different TMP assumptions and crop mix on N input projection.

In addition to these causes, discrepancies in projections could arise due to the uncertainties associated with the data sources. Our analysis relied on the dataset complied by Food and Agricultural Organization of the United Nations Statistical Database (FAOSTAT [46]), but recent studies have demonstrated that large discrepancies exist among different datasets for N budget estimates such as N in harvested crop [33, 34]. We chose FAOSTAT as the primary data source for this study because it has good spatio-temporal coverage, which is critical for the global scale analysis in this study. Using the same database for the projection under different scenarios will minimize the impact of different input data. However, further investigation on the discrepancies among various data sources developed from different spatial scales is needed to address these discrepancies and their impacts on the N input projection.

4.3. Implications for crop N management

Crop N management is facing tremendous challenges in the next three decades. The projections in this study suggest that N inputs will continue to increase by 59 Tg N yr^{-1} (115 Tg N yr^{-1} for N surplus and 0.49 for NUE) globally, even if TMP keeps improving at the pace of past decades. To meet the food demand and bring N surplus back to planetary boundary, Zhang *et al* [31] proposed a set of NUE goals for countries and crops. Comparing to those goals, most of our projected NUEs are still much lower even with the 'Improving TMP' approach (assuming the TMP improves at the pace of past decades) (SI text S9). For instance, NUE of China (0.43), Brazil (0.57) and India (0.29) in the 'Improving TMP' approach are significantly lower than the NUE goals of 0.60, 0.70, and 0.60, respectively (see SI figure S7). Among the 11 crop classes, fruits and vegetables and sugar crops are those require the largest NUE improvement to meet the NUE goals. Even the major cereal crops (i.e. wheat, rice, and maize) have NUE (0.50, 0.44, and 0.53, respectively) in the 'Improving TMP' approach lower than the NUE goals (0.70, 0.60, and 0.70, respectively). The comparison indicates the priority regions as well as crop classes that require accelerated improvement in TMP development and adaptation.

However, even keeping the pace of TMP improvement is challenging in most countries. For example, significant progress has been made in developing and adopting TMP in many developed countries. USA and European Union (EU) have managed to increase NUE from 44% in 1980s to 62% in 2010s while maintaining and increasing yield through adopting TMP such as '4Rs' principles [47] and improved crop cultivars [48]. However, such improvement has been heavily relying on market incentives (e.g. fertilizer tax, subsidy for enhanced efficiency fertilizer) in the USA and strong regulations at EU, and it is not clear whether those mechanisms will continue to be effective in the coming decades given the volatile crop and energy markets. In contrast, SSA countries are still at the early intensification stage, with low N inputs and high NUE. With projected increase in crop production, more N inputs and lower NUE are expected based on the development trajectories exhibited by most developed and developing countries around the world [31]. Changing such trajectories for crop intensification in SSA would require yield increase relying more on TMP improvement than input increase, which is challenging for least developed countries with very limited resources [2, 44]. Continuously improving and implementing TMP is also facing challenges in developing countries such as China and India, where inefficient use of fertilizer has already led to various N pollution issues. Heavily subsidized fertilizer provides limited incentives for farmers to adopt more N-efficient TMP, although phasing out subsidies need to be balanced with food security and social well-being concerns for rural communities.

In addition to the challenges in maintaining or even accelerating the momentum of TMP improvement in countries, challenges also exist in the changing ecological conditions for cropland around the world. Besides TMP, the changes in climate and soil conditions can affect yield response to N inputs. For example, increasing heat stress caused by global warming might stagnate the yield of major cereal crops even after implementing management practices [49–51]. These impacts need to be assessed and addressed in future studies. These challenges for crop N management are also accompanied by opportunities. There have been a wide range of TMP available for improving N management on farms, and many of them are associated with low implementation cost. In addition, governments and international communities have increasingly recognized the adverse impacts of inefficient N use not only on ecosystem health but also on human health and the economy [52], and consequently, an increasing number of countries have put forward policies and targets to curtail N inputs in agricultural production (e.g. the 'Zero growth' goal for fertilizer consumption set by the Chinese government [53];. Finally, despite the recent set-back by the COVID-19 pandemic and the

rise of deglobalization movements, international collaboration and open science-sharing will continue to help accelerating the TMP improvement across countries.

5. Conclusions

The approach for projecting N inputs under the BAU or reference scenario by assuming NUE staying at the current level results in a much lower projection in N inputs than the projection considering the diminishing return of yield to N inputs under the same TMP. The optimistic projection by the constant NUE approach can be potentially achieved by keep improving TMP at the pace of past decades, but sustaining the improvement faces multiple challenges such as climate change. In addition, even with the optimistic projection of keeping NUE constant or steadily improving TMP, N inputs and N surplus are projected to increase by 2050, and projected NUE is lower than the NUE goal set for meeting the dual challenges of food demand and N pollution by 2020, further highlighting the urgent need for accelerating the development and implementation of TMP around the world. The comparison among N inputs projected with different approaches in this study demonstrates the importance of assumptions made in BAU scenarios, and also highlights countries (e.g. India, Brazil, and Pakistan) and crop classes (e.g. fruits and vegetables, and sugar Crops) that need to be prioritized for improving NUE and TMP.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was supported by the National Science Foundation CNS-1739823, and National Socio-Environmental Synthesis Center (SESYNC) under funding received from the National Science Foundation DBI-1639145. X Z is also supported by the National Science Foundation CBET-2047165, and CBET-2025826. Data used for the analysis are available via Zhang *et al* [31] and Zhang *et al* [33].

ORCID iDs

Srishti Vishwakarma https://orcid.org/0000-0003-1674-4197
Xin Zhang https://orcid.org/0000-0003-1619-1537
Nathaniel D Mueller https://orcid.org/0000-0003-1857-5104

References

[1] Lassaletta L, Billen G, Garnier J, Bouwman L, Velazquez E, Mueller N D and Gerber J S 2016 Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand *Environ. Res. Lett.* **11** 1–14
[2] Sutton M A *et al* 2013 Our nutrient world: the challenge to produce more food and energy with less pollution (Global Overview of Nutrient Management, Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership)
[3] Hong C, Burney J A, Pongratz J, Nabel J E M S, Mueller N D, Jackson R B and Davis S 2021 Global and regional drivers of land-use emissions in 1961–2017 *Nature* **589** 554–61
[4] Steffen W *et al* 2015 Planetary boundaries: guiding human development on a changing planet *Science* **348** 1217–c
[5] Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management *Nature* **490** 254–7
[6] Sinclair T R and Rufty T W 2012 Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics *Glob. Food Secur.* **1** 94–98
[7] Tittonell P, Vanlauwe B, Corbeels M and Giller K E 2008 Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya *Plant Soil* **313** 19–37
[8] Rurinda J *et al* 2020 Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa *Agric. Syst.* **180** 102790
[9] ten Berge H F M *et al* 2019 Maize crop nutrient input requirements for food security in sub-Saharan Africa *Glob. Food Secur.* **23** 9–21
[10] Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
[11] Hunter M C, Smith R G, Schipanski M E, Atwood L W and Mortensen D A 2017 Agriculture in 2050: recalibrating targets for sustainable intensification *Bioscience* **67** 386–91
[12] Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–4
[13] Doelman J C *et al* 2018 Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation *Glob. Environ. Change* **48** 119–35
[14] Erisman J W, Sutton M A, Galloway J, Klimont Z and Winiwarter W 2008 How a century of ammonia synthesis changed the world *Nat. Geosci.* **1** 636–9
[15] Bodirsky B L *et al* 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution *Nat. Commun.* **5** 3858
[16] Bouwman L, Goldewijk K K, Van Der Hoek K W, Beusen A H W, Van Vuuren D P, Willems J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period *Proc. Natl Acad. Sci.* **110** 20882–7
[17] Liu J, Ma K, Ciais P and Polasky S 2016 Reducing human nitrogen use for food production *Sci. Rep.* **6** 1–14
[18] Mogollón J M, Lassaletta L, Beusen A H W, van Grinsven H J M, Westhoek H and Bouwman A F 2018 Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways *Environ. Res. Lett.* **13** 044008
[19] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68
[20] Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision (Rome: FAO)
[21] Cassman K G, Dobermann A, Walters D T and Yang H 2003 Meeting cereal demand while protecting natural resources and improving environmental quality *Annu. Rev. Environ. Resour.* **28** 315–58

[22] Wood S, Henao J and Rosegrant M 2004 The role of nitrogen in sustaining food production and estimating future nitrogen fertilizer needs to meet food demand *Agric. nitrogen cycle Assess. impacts Fertil. use food Prod. Environ.* (Washington: Island Press) pp 245–60
[23] Lassaletta L, Billen G, Grizzetti B, Anglade J and Garnier J 2014 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
[24] Zhang X, Mauzerall D L, Davidson E A, Kanter D R and Cai R 2015 The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture *J. Environ. Qual.* **44** 312
[25] Below F E, Uribelarrea M, Company M and Moose S P 2007 Triple-stacks, genetics and biotechnology in improving nitrogen use of corn *North Cent. Extension-Industry Soil Fertil. Conf. (Des Monies, IA)*
[26] Gehl R J, Schmidt J P, Maddux L D and Gordon W B 2005 Corn yield response to nitrogen rate and timing in sandy irrigated soils *Agron. J.* **97** 1230–8
[27] Mueller N D, Lassaletta L, Runck B C, Billen G, Garnier J and Gerber J S 2017 Declining spatial efficiency of global cropland nitrogen allocation *Glob. Biogeochem. Cycles* **31** 245–57
[28] Billen G, Lassaletta L and Garnier J 2015 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
[29] Billen G, Lassaletta L and Garnier J 2014 A biogeochemical view of the global agro-food system: nitrogen flows associated with protein production, consumption and trade *Glob. Food Secur.* **3** 209–19
[30] Billen G *et al* 2021 Reshaping the European agro-food system and closing its nitrogen cycle: the potential of combining dietary change, agroecology, and circularity *Sci. Data* **8** 839–50
[31] Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P and Shen Y 2015 Managing nitrogen for sustainable development *Nature* **528** 51–59
[32] Huang G, Yao G, Zhao J, Lisk M D, Yu C and Zhang X 2019 The environmental and socioeconomic trade-offs of importing crops to meet domestic food demand in China *Environ. Res. Lett.* **14** 94021
[33] Zhang X *et al* 2021 Quantification of global and national nitrogen budgets for crop production *Nat. Food* **2** 529–40
[34] Zhang J, Cao P and Lu C 2021 Half-century history of crop nitrogen budget in the conterminous United *Glob. Biogeochem. Cycles* **35** e2020GB006876
[35] Heffer P 2009 Assessment of fertilizer use by crop at the global level (Paris)
[36] Jaynes D B 2011 Confidence bands for measured economically optimal nitrogen rates *Precis. Agric.* **12** 196–213
[37] Cerrato M E and Blackmer A M 1990 Comparison of models for describing; corn yield response to nitrogen fertilizer *Agron. J.* **82** 138
[38] Paris Q 1992 The von Liebig Hypothesis *Am. J. Agric. Econ.* **74** 1019
[39] Wendling Z A, Emerson J W, Esty D C, Levy M A, de Sherbinin A and Al. E 2018 Environmental performance index 2018
[40] Dobermann A and Cassman K G 2005 Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption *Sci. China* C **48** 745–58
[41] Thomas T S 2018 Changes in food supply and demand by 2050 *Food Security and Climate Change* 1st edn (Hoboken, NJ: John Wiley & Sons) pp 25–50
[42] Ertl P, Zebeli Q, Zollitsch W and Knaus W 2015 Feeding of by-products completely replaced cereals and pulses in dairy cows and enhanced edible feed conversion ratio *J. Dairy Sci.* **98** 1225–33
[43] Erisman J W, Leach A, Bleeker A, Atwell B, Cattaneo L and Galloway J 2018 An integrated approach to a nitrogen use efficiency (NUE) indicator for the food production-consumption chain *Sustainability* **10** 1–29
[44] Kanter D R, Bartolini F, Kugelberg S, Leip A, Oenema O and Uwizeye A 2020 Nitrogen pollution policy beyond the farm *Nat. Food* **1** 27–32
[45] De Vries W, Kros J, Kroeze C and Seitzinger S P 2013 Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts *Curr. Opin. Environ. Sustain.* **5** 392–402
[46] FAOSTAT 2019 Food and Agricultural Organization of the United Nations Statistical Database (available at: www.fao.org/faostat/en/#data/TCL) (Accessed 27 Mar 2019)
[47] International Fertilizer Association (IFA) 2009 The Global 4R Nutrient Stewardship Framework (Paris)
[48] Ferguson R B 2015 Groundwater quality and nitrogen use efficiency in Nebraska's Central Platte River Valley *J. Environ. Qual.* **44** 449–59
[49] Iizumi T, Furuya J, Shen Z, Kim W, Okada M, Fujimori S, Hasegawa T and Nishimori M 2017 Responses of crop yield growth to global temperature and socioeconomic changes *Sci. Rep.* **7** 1–10
[50] Lobell D B and Gourdji S M 2012 The influence of climate change on global crop productivity *Plant Physiol.* **160** 1686–97
[51] Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci. USA* **111** 3268–73
[52] Compton J E, Leach A M, Castner E A and Galloway J N 2017 Assessing the social and environmental costs of institution nitrogen footprints *Sustainability* **10** 114–22
[53] Ju X, Gu B, Wu Y and Galloway J N 2016 Reducing China's fertilizer use by increasing farm size *Glob. Environ. Change* **41** 26–32