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

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Key Points:

- We utilized yield response functions to project nitrogen inputs in 2050.
- We found that conventional approaches are too optimistic in projecting nitrogen inputs.
- We call for the consideration of diminishing return in yield response to nitrogen inputs and the impact of crop mixes in projection methods.

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. To project future N inputs for crop production, many studies assumed that Nitrogen Use Efficiency (NUE) remains the same as the current level under a Business-As-Usual (BAU) scenario. This assumption ignores potential NUE changes caused by shifting crop mixes and the diminishing return of yield increase to N inputs at a given level of technology and management practices (TMP). To evaluate the impacts of these two factors on the projection of future N inputs, we developed and tested three approaches, namely "Same NUE", "Same TMP", and "Improving TMP". We found that the approach considering the diminishing returns in yield response ("Same TMP") resulted in 268 Tg N yr^{-1} of N inputs which were 61 and 48 Tg N yr^{-1} higher when keeping NUE at the current level with and without considering crop mix, respectively. If TMP is assumed to continue to evolve at the pace of past five decades, the projected N inputs reduce to 204 Tg N yr^{-1}, but still 59 Tg N yr^{-1} higher than the inputs in the baseline year 2006. Overall, our results suggest that the BAU approach that assumes 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 (Lassaletta et al., 2016), boosting crop yields while leading to adverse environmental impacts from regional to global scales. It is reported that the global N inputs have already exceeded the so-called "planetary boundary", which marks the safe operating space for humanity, by over 83–142% (Steffen et al., 2015). 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 (Mueller et al., 2012; Sinclair & Rufty, 2012; Tittonell, Vanlauwe, Corbeels, & Giller, 2008). To meet rising food demand, global crop production is projected to increase by 60–110% by 2050 compared to 2005 baseline (Foley et al., 2011; Hunter, et al., 2017; Tilman, et al., 2011), suggesting continuous demand for N inputs worldwide. But whether, where, and by how much N inputs will continue to increase are critical to understand for future environmental sustainability and food security.

To project the 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 (Bodirsky et al., 2014; Bouwman et al., 2013; Liu, Ma, Ciais, & Polasky, 2016). Among these studies, most include a projection under "Business-As-Usual" (BAU) as a reference scenario, which considers that the state of affairs stays unchanged. One of the assumptions that have been widely used to quantitatively project N inputs under the BAU scenario is that NUE stays constant at the current level when meeting the projected future crop demand (Cassman, Dobermann, Walters, & Yang, 2003; Wood, Henao, & Rosegrant, 2004).

There are two major concerns about this widely used assumption. First, assuming a constant NUE at a much higher production level ignores the diminishing return of yield response to N inputs. Here, diminishing return means stagnating crop yield with increasing N inputs. This concept is often implemented at farm-scale agronomic research (Below, Uribelarrea, Company, & Moose, 2007; Ciampitti, Zhang, Friedemann, & Vyn, 2012; Gehl, Schmidt, Maddux, & Gordon, 2005; Gentry, Ruffo, & Below, 2013; Haegele & Below, 2013; Zhang, Mauzerall, Davidson, Kanter, & Cai, 2015); but has been implemented in a few national or global scale analyses and N inputs projection recently (e.g., Lassaletta et al., 2016; Mogollón et al., 2018; Mueller et al., 2017).

Second, most projection approaches 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 (Zhang, Davidson, et al., 2015). Such differences among crop classes is 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 (Huang et al., 2019), while the aggregated NUE in China for year 2010 was 0.20–0.30 (Lassaletta et al., 2016; Zhang, Davidson, et al., 2015). Hence, using aggregated NUE instead of crop-specific NUE will likely introduce bias to the projection of future N inputs.

To address these concerns, we update and use a unique database of N budgets by country and crop classes; 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

To enable the N inputs projection considering crop categories, we 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 to 2015 based on the methodologies developed by Zhang, Davidson, et al. (2015). Total N inputs to cropland included N-fertilization, N-fixation and N-deposition in kg N ha^{-1} yr^{-1}, while the output included crop yield in kg N ha^{-1} yr^{-1} representing N in harvested crop. The analysis was performed for 115 countries or regions (see the list of the countries in SI Table S1; Zhang, Davidson, et al., 2015), and 11 crop classes (wheat, rice, maize, soybean, Other Coarse Grain, Oil Palm, Other Oil Seeds, Sugar Crops, cotton, Fruits and Vegetables, and Other Crops) following International Fertilizer Association's (IFA) guidelines (Heffer, 2009). The list of countries or regions were based on the list of major crop producing countries used in Zhang, Davidson, et al. (2015) for statistical assessment, adding Argentina and Former Soviet Union (FSU). The FSU countries which split after 1991 were aggregated together and treated as a single region in this study.

Projections of crop yield and harvested area for year 2050 were from Food and Agricultural Organization of the United Nations (FAO) 2012 report (Alexandratos & Bruinsma, 2012) with baseline year of 2006 (averaged 2005–2007). The projected crop yield is expressed in kg N ha^{-1} yr^{-1}.

2.2 Assumptions and approaches for projection

We designed three approaches to project N inputs in 2050 based on the same projected crop demand but different assumptions for NUE under a BAU scenario (Table 1). The first approach, named "Same NUE", assumes that NUE stays the same as the current level (i.e., averaged NUE for 2011–2015); the second approach, "Same TMP," considers the technology and management practices (TMP, represented by the yield response to N inputs for each country and crop classes) stay the same as the current level (i.e., determined by observations from 2006 to 2015); while the third approach "Improving TMP," assumes TMP keeps evolving following the pace and trajectory observed in the past decades (1961–2015).

Table 1: Summary of projection approaches and their assumptions

Projection Approaches	Assumptions
Same NUE	NUE for each crop type and country stay the same at current level (i.e., averaged NUE for 2011–2015) With and without* crop mixes
Same TMPs	The yield response function, representing the level of technologies and management practices (TMPs) as well as environmental conditions, stays the same as the current level (i.e., determined by observations from 2006 to 2015)
Improving TMPs	The yield response function keeps evolving following the pace and trajectory observed in the past decades (1961–2015)

*aggregated NUE

2.2.1 "Same NUE" approach

With this approach, we used NUE by country (k) and crop classes (c) for recent years to project N inputs in 2050, assuming NUE stays the same (Figure 1a). This approach does not consider the diminishing return of crop yield to N inputs under the same ecological and TMP conditions. We first estimated the NUE for each country and crop classes for the 2011–2015 period. Using the estimated NUE, we calculated N input rates using crop yields in 2050 as projected by the FAO 2012 report (Alexandratos & Bruinsma, 2012; equation 1). We then are able to calculate total N inputs quantity in 2050 using the harvested area from the same report (Alexandratos & Bruinsma, 2012; equation 2)

$$I_{k,c,t=2050} = \frac{Y_{k,c,t=2050}}{NUE_{k,c,t=2011:2015}} \quad (1)$$

$$TN_{k,c,t=2050} = I_{k,c,t=2050} H_{k,c,t=2050} \times 10^{-9} \quad (2)$$

where $NUE_{k,c,t}$ is NUE, is N input rates (sum of fertilizer, biological fixation, atmospheric deposition, and manure), $Y_{k,c,t}$ $(kg\ N\ ha^{-1} yr^{-1})$ is N yield, $TN_{k,c,t}$ $(Tg\ N\ yr^{-1})$ is total quantity of N inputs, $H_{k,c,t}$ (ha) is harvested area, and t is the year.

In order to investigate the impacts of crop mixes on the projection of N inputs, we tested the projection with the aggregated NUE of all 11 crop classes (the full list of crop classes and their definition could be found in Table S2 in SI) in a country for the 2011–2015 period. Then, we calculated N input rates in 2050 using the estimated NUE and projected yield in 2050 (equation 3), and then calculated total N input quantity with projected harvested area in 2050 (equation 4).

$$I_{k,t=2050} = \frac{Y_{k,t=2050}}{NUE_{k,t=2011:2015}} \quad (3)$$

$$TN_{k,t=2050} = I_{k,t=2050} H_{k,t=2050} \times 10^{-9} \quad (4)$$

where $NUE_{k,t}$ is NUE, $I_{k,t}$ $(kg\ N\ ha^{-1}yr^{-1})$ is N input rates (sum of fertilizer, biological fixation, atmospheric deposition, and manure), $Y_{k,t}$ $(kg\ N\ ha^{-1}yr^{-1})$ is N yield, $TN_{k,t}(Tg\ N\ yr^{-1})$ is total quantity of N inputs, $H_{k,t}$ (ha) is harvested area, and t is the year.

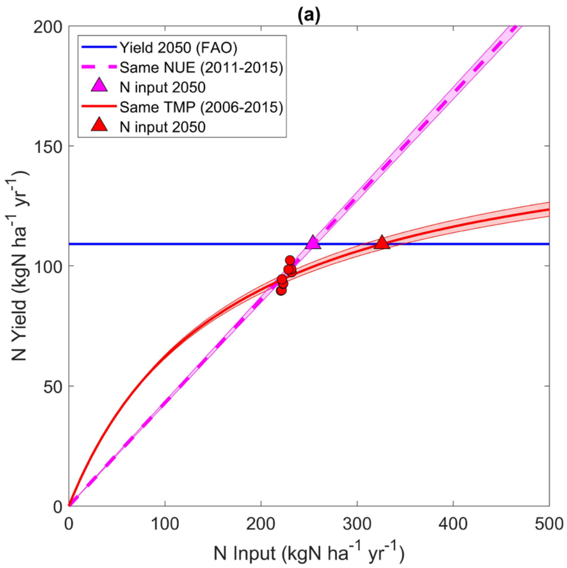

Figure 1: Illustration of projection approaches using N use data for China's wheat production as an example. The projected N inputs are shown as colored triangles: Pink and red triangles for "Same NUE" and "Same TMP" approaches (panel a) and grey triangles for "Improving TMP" approach (panel b). The 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: Red and grey lines for "Same TMP" (2006–2015) (panel a) and "Improving TMP" approaches, while other green lines in panel b are yield response relationships for different period from 1961–2015. The shaded area around lines is the 95% confidence interval estimated using 1000X bootstrap resampling. The blue horizontal line is the 2050 yield target obtained from FAO 2012 report.

2.2.2 "Same TMP" approach

In contrast to the "Same NUE" approach, "Same TMP" approach considers that 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 and they typically have three properties: (1) a low or zero intercept, (2) at low N inputs the slope of the function is at or near 1, and (3) at high N inputs the function will achieve a plateau (Lassaletta, Billen, Grizzetti, Anglade, & Garnier, 2014; Mueller et al., 2017). Typical forms of yield response functions include quadratic plateau, exponential, Mitscherlich-Baule and one-parameter hyperbolic (Cerrato & Blackmer, 1990; Jaynes, 2011; Lassaletta et al., 2014; Paris, 1992)

Based on the N inputs and yield records for the most recent ten years (i.e., 2006 to 2015) we first estimated a yield response function for each country and crop class (equation 5; Figure 1a). Then, we used these yield response functions to estimate N input rates when yield changes to 2050 level (equation 6). In this study, we used one-parameter hyperbolic function as the yield response function, which can easily be parameterized on a country scale using annual data (Lassaletta et al., 2016, 2014; Mogollón et al., 2018; Mueller et al., 2017).

$$Y_{k,c,t} = M_{k,c,t=2006:2015} \frac{I_{k,c,t}}{M_{k,c,t}+I_{k,c,t}} \quad (5)$$

where $M_{k,c,t}$ ($kg\ N\ ha^{-1}yr^{-1}$) is the coefficient of a one-parameter hyperbolic yield response function representing maximum obtainable yield.

$$I_{k,c,t=2050} = \frac{M_{k,c,t=2006:2015} Y_{k,c,t=2050}}{M_{k,c,t=2006:2015} - Y_{k,c,t=2050}} \quad (6)$$

Using the projected N input rates and harvested area in 2050, we estimated total N inputs quantity ($TN_{k,c,t}$) in 2050 (equation 2).

2.2.3 **"Improving TMP" approach**

In the "Improving TMP" approach, we assume TMP improve at the rate observed over recent decades. 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 (i.e., 1961–70, 1971–80, 1981–90, 1991–2000, 2001–2010 and 2011–15) (Figure 1b). 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 (Lassaletta et al., 2014). Larger values of the coefficient demonstrate improvement in TMP, and vice-versa (Mogollón et al., 2018). Consequently, we used $M_{k,c,t}$ for the past six time periods to extrapolate to 2050 and estimate $M_{k,c,t=2050}$.

The extrapolation of $M_{k,c,t}$ was first conducted by fitting a linear relationship to the observations for the six time periods. While majority of the country and crop classes show increasing trends and $M_{k,c,t=2050}$ is projected by linear extrapolation, some have shown decreasing trend. For those cases with a decreasing trend, we first fit a quadratic function to the observations for the six periods, and use the function to project 2050 level when the function shows a "U" shape relationship between time and $M_{k,c,t}$ (e.g., wheat production in Argentina, Figure 2a). For the remaining cases (e.g., Sugar Crop production in Nigeria, Figure 2b), we assume $M_{k,c,t}$ stay the same as the current level (i.e.,$M_{k,c,t=2006:2015}$), which is equivalent to the "Same TMP" approach.

$$M_{k,c,t=2050} = \begin{cases} \beta t + C, & (\beta > 0) \\ \beta_1 t^2 + \beta_2 t + C, & (\beta \le 0\ \ \&\ \beta_1 > 0\ \ \& -\beta_2/2\,\beta_1 \le 2011) \\ M_{k,c,t=2006:2015}, & (otherwise) \end{cases} \quad (7)$$

where t = 2050, β, β_1, β_2 and C are obtained for each country and crop class by fitting either linear or quadratic relationship to the six records of $M_{k,c,t}$

Consequently, we can project N input rates according to equation 6 by replacing $M_{k,c,t=2006:2015}$ with $M_{k,c,t=2050}$, and calculate total N inputs quantity ($TN_{k,c,t}$) using equation 2.

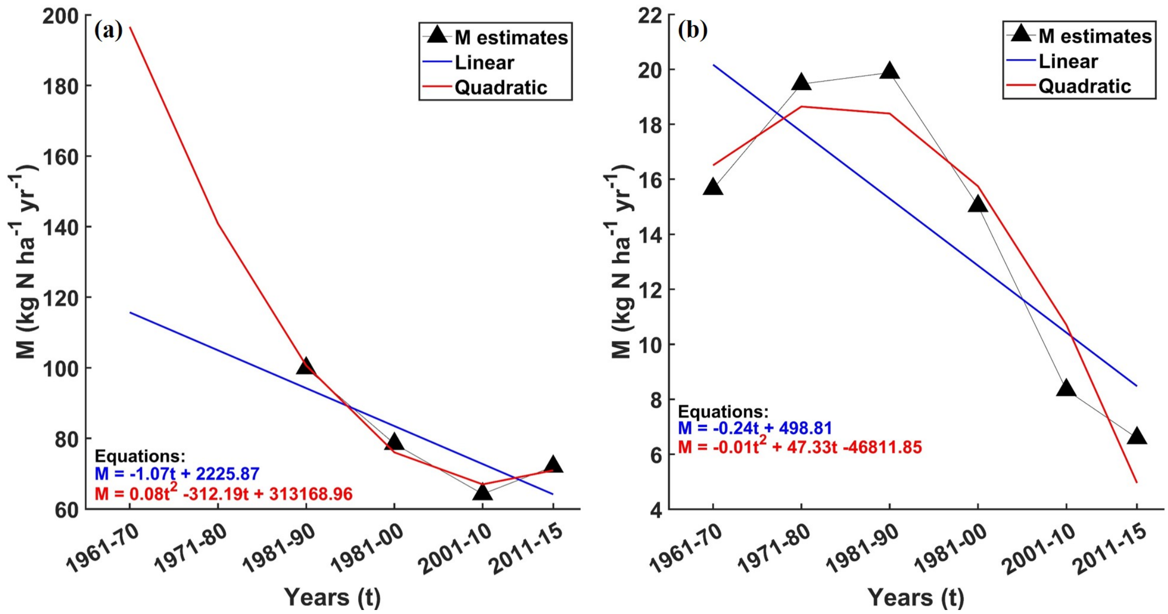

Figure 2: Illustration of relationship of M vs year set used in the "Improving TMP" approach; Argentina wheat (panel a), and Nigeria Sugar crops (panel b). The black triangle and line shows the values of coefficient M for each chosen period (x-axis). The blue line shows the linear fit of M vs year, while red line shows quadratic fit. Expression of equations are also shown in each panel with font color corresponds to the linear (quadratic) fit.

One-parameter hyperbolic yield response function has a coefficient $M_{k,c,t}$ which exhibits the maximum yield of a cropping system. However, it is possible that the projected 2050 yield ($Y_{k,c,t=2050}$) from FAO 2012 report (Alexandratos & Bruinsma, 2012) could be higher than the coefficient $M_{k,c,t}$. For these cases, the projected yield could not be achieved with the existing yield response function (or existing TMP), even if N inputs keep increasing. Consequently, for each country and crop class, we use the 95th percentile of N inputs for 2011 to 2015 period as the upper bound of projected N input rates (see Supplementary Table S2 for the values of 95th percentile of N inputs). The flow diagrams of the "Same TMP" and "Improving TMP" approach are presented in Supplementary Figures S1, S2, S3, and S4.

2.3 Uncertainty tests

We examined two potential sources of uncertainties for projected N inputs: 1) the uncertainty associated with estimated parameters in the yield response function, and 2) the effect of using different yield response functions.

2.3.1 Uncertainty quantification of projected N inputs

To identify an uncertainty range of projected N inputs, we performed a bootstrap resampling (1000X) of each country and crop combination's N input and N yield data, recalculating the relevant parameters for each projection approach in order to estimate 95% confidence intervals. For each set of resampled data, we estimated $NUE_{k,c,t=2011:2015}$ in the "Same NUE" approach, while fitting yield response functions for the "Same TMP" and "Improving TMP" approaches to estimate the coefficients $M_{k,c,t=2006:2015}$ and $M_{k,c,t=2050}$, respectively. These iterations provided a distribution of the estimates for $NUE_{k,c,t=2011:2015}$, $M_{k,c,t=2006:2015}$ and $M_{k,c,t=2050}$, from which we calculated the 95% confidence intervals. Using the 95% confidence interval of

$NUE_{k,c,t=2011:2015}$, $M_{k,c,t=2006:2015}$ and $M_{k,c,t=2050}$, we estimated the uncertainty range of projections of N inputs rates and quantity.

In the "Improving TMP" approach, since yield response functions are for different time periods, we simultaneously resampled each time period and estimated 95% confidence interval $M_{k,c,t}$ corresponding to each period (Figure 1b). Then, using the confidence interval of $M_{k,c,t}$, we estimated the confidence interval of N input projection.

2.3.2 The effect of using different yield response functions

In addition to the hyperbolic function, we tested the quadratic-plateau yield response function, which is frequently used on the farm scale (Jaynes, 2011; Sawyer et al., 2006; Zhang, Mauzerall, et al., 2015), and examined the impacts of function choice on the N projection outcome. We tested two methods for parameterizing the quadratic-plateau function: 1) using N inputs and yield records to fit the function and estimate parameters, and 2) derive the parameters for the quadratic plateau yield response function based on the N inputs, yield and fertilizer-to-crop price ratio records for a given year (see Text S6 and S7 of SI for details). Constrained by data availability, the second method was only applied to a handful of countries and staple crops (wheat, rice, maize, and soybean) only. The estimated yield response functions were used to project N inputs with the "Same TMP" and "Improving TMP" approaches.

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 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, 0.38 (0.34–0.40), and higher N surplus, 168 (153–194) Tg N yr^{-1}, by the "Same TMP" approach than those projected by the "Same NUE" approach (Table 2). This demonstrates that the 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 6.30%) 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.

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	268 [254 295]	0.38 [0.34 0.40]	168 [153 194]
Improving TMP	One-parameter hyperbolic	204 [196 229]	0.49 [0.44 0.51]	103 [95 128]

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

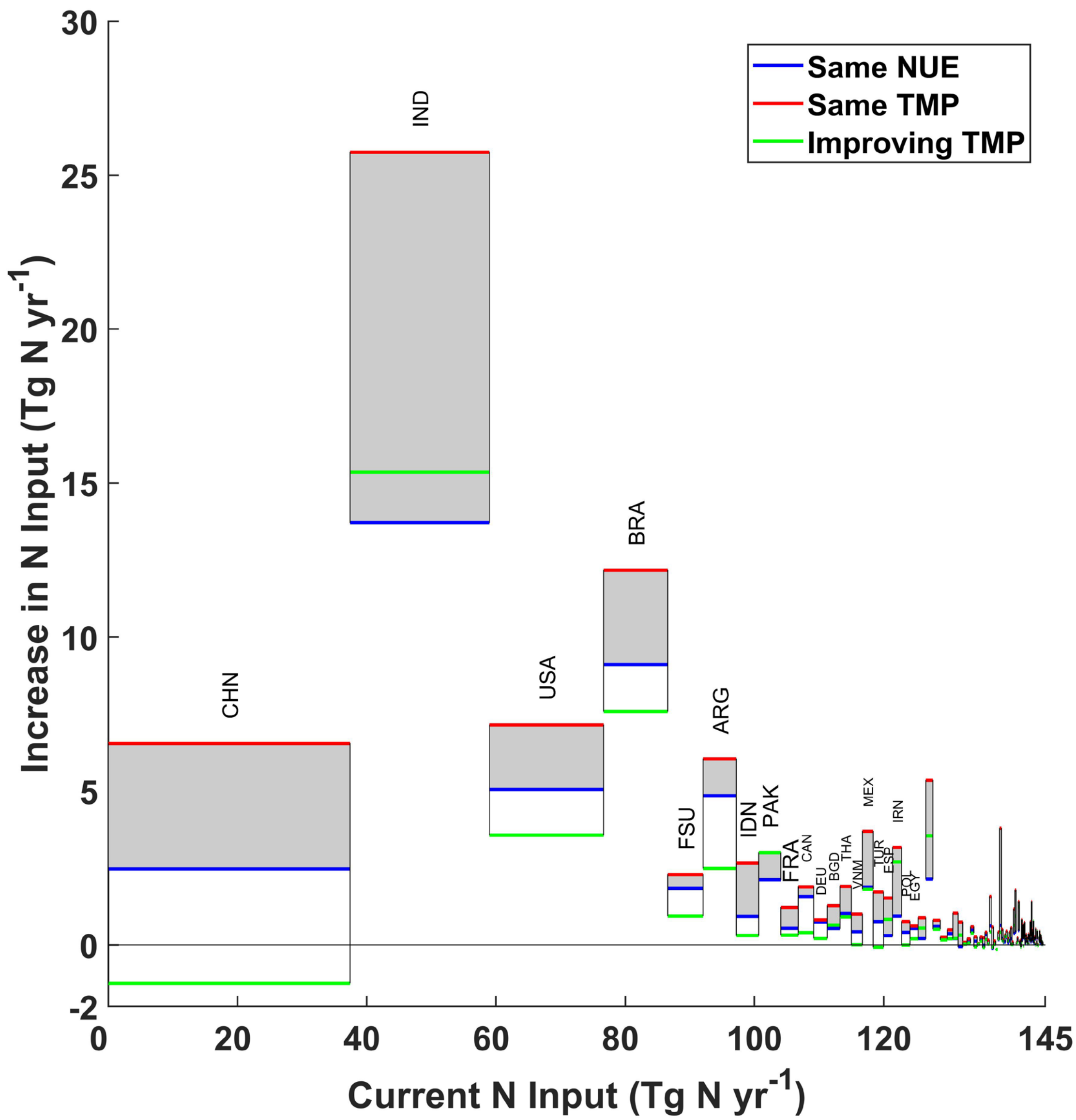

Figure 3: Projected country-level increase (decrease) in N inputs from baseline year 2006 (average 2005–2007). Each box represents a country. The horizontal lines in the box shows the changes in projected N inputs from baseline, while the width of the line shows the N input in the baseline. The filled 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. Each country is represented by the three letter acronym following the definition of ISO alpha-3 country code (ISO 3166-1: 2013). 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.

3.2 Regional N inputs differences

Most countries around the world project increase in N inputs from baseline year to 2050 despite approaches used in this study (Figure 3). 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 eight world regions (Wendling et al., 2018), 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. 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 (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 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.

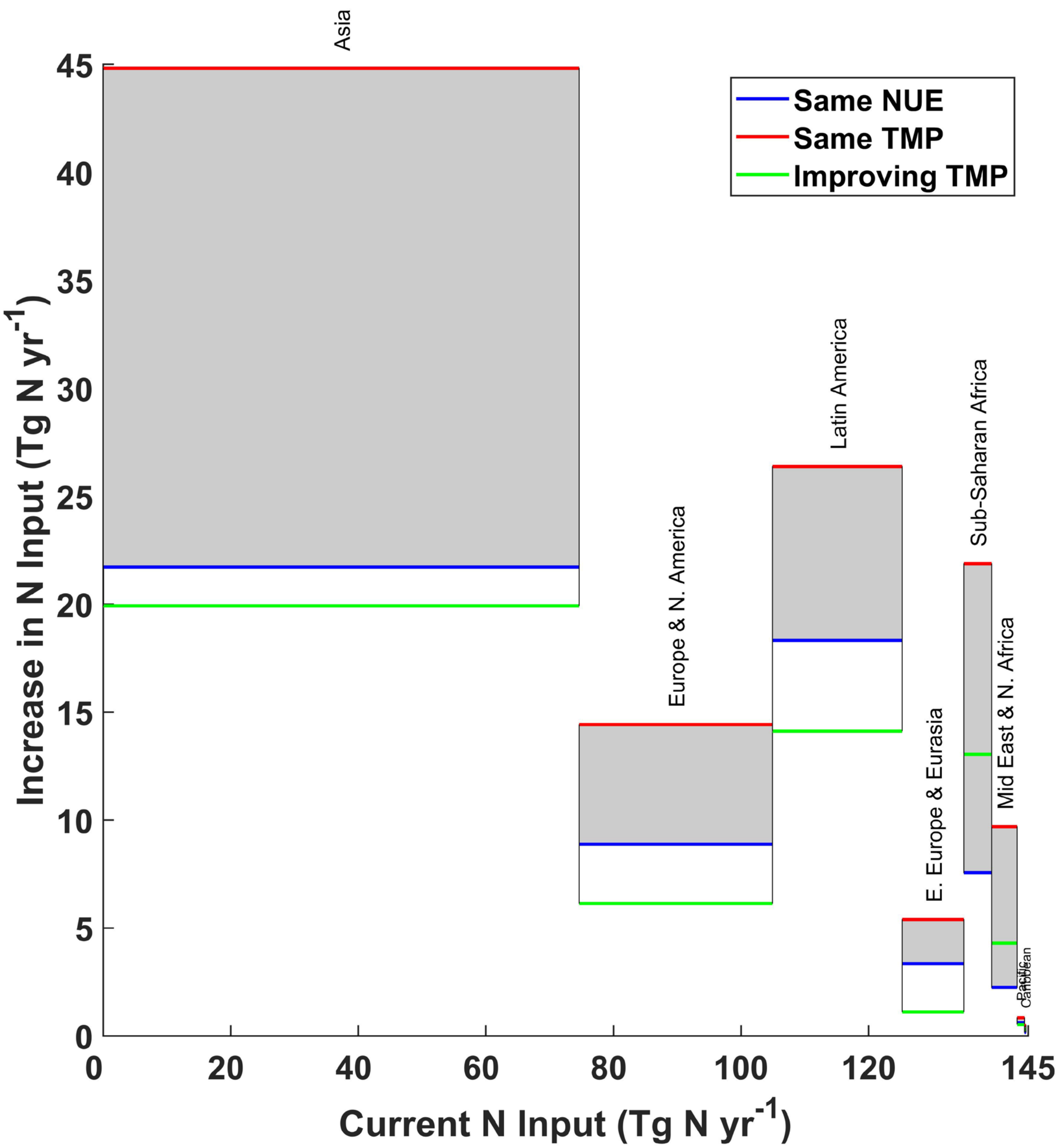

Figure 4: Projected regional-level increase (decrease) in N inputs from baseline year 2006 (average 2005–2007). Each box represents a region. The horizontal lines in the box shows the changes in projected N inputs from baseline, while the width of the line shows the N input in the baseline. The filled 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.

3.3 Crop specific N inputs differences

Despite the approaches used for projection, N inputs for each of the eleven crop groups will increase. However, the level of projected increase varies largely, attributing to not only the different increases in production levels but also the different projection approaches (Figure 5). 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): despite the 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; NUE for rice, wheat and maize ranges from 0.35 to 0.53; and Fruits and Vegetables and Sugar Crops showed the lowest NUE 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 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.

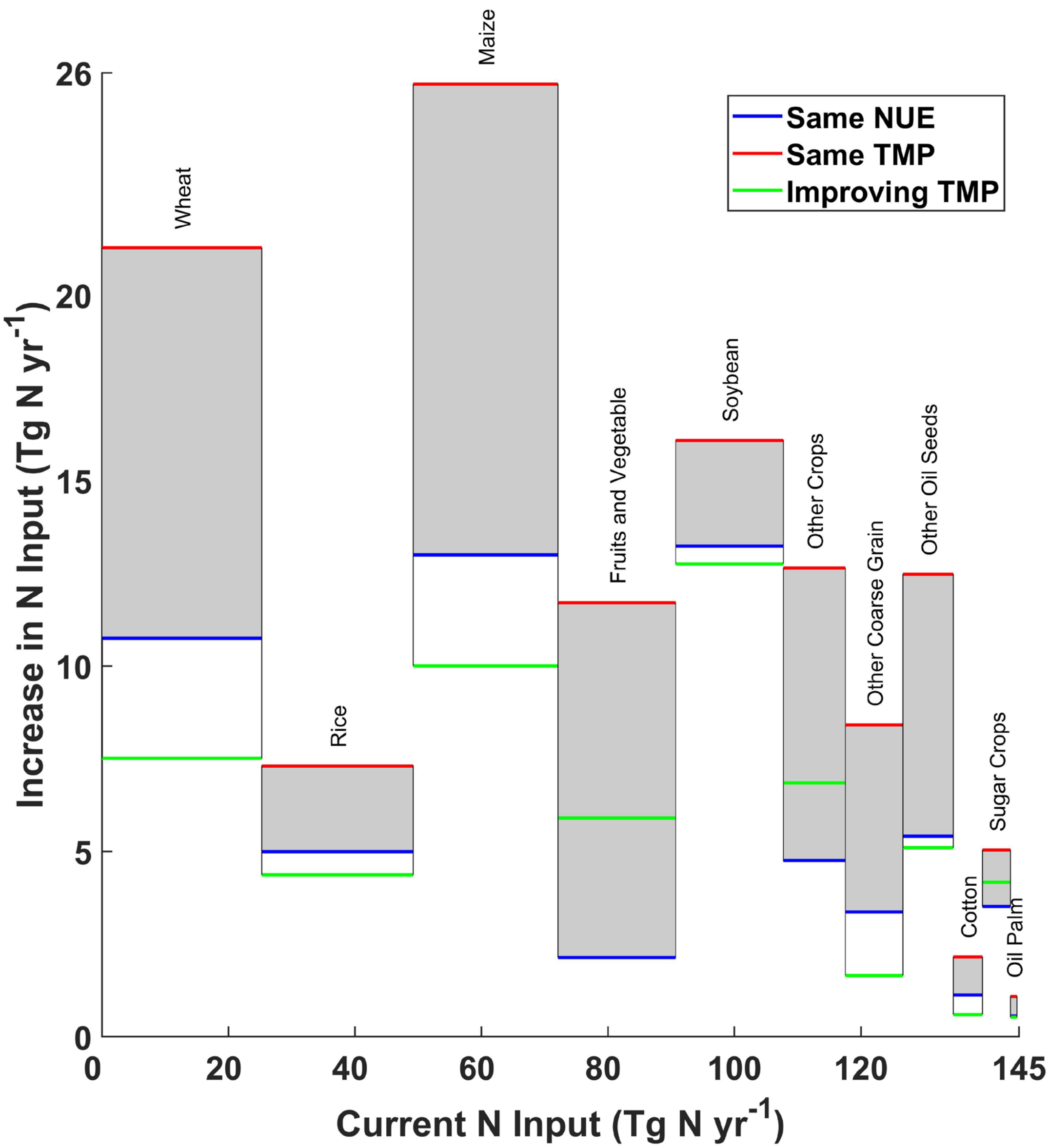

Figure 5: Projected crop-level increase (decrease) in N inputs from baseline year 2006 (averaged 2005–2007). Each box represents a crop type. The horizontal lines in the box shows the changes in projected N inputs from baseline, while the width of box shows the N input in the baseline. The filled grey 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.

4 Discussion

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 (Zhang, Mauzerall, et al., 2015). Applying this theory of diminishing return to a broader spatial scale (Lassaletta et al., 2014; Mueller et al., 2017) 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.

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 (Alexandratos & Bruinsma, 2012), soybean production (with world average NUE of 0.80; Zhang, Davidson, et al., 2015) will increase by 80%, requiring less N inputs per unit of crop product than other crops. But the NUE increase due to the expanding soybean is compromised by the continuous expansion of Fruits and Vegetables production (with world average NUE at 0.14; Zhang, Davidson, et al., 2015), which is projected to increase more than 80% (Thomas, 2019). In addition, the current increase in soybean production is mostly used for animal feeds, and such usage will reduce the efficiency of N use in the food supply chain, 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 (Erisman et al., 2018; Kanter, Bartolini, et al., 2020; Sutton et al., 2013).

Uncertainties in the projection

Two major sources of uncertainties are considered in this study: one is the uncertainty associated with the parameters in the yield response function derived from historical records, the other is the choice of the yield response function format. While we evaluated the first source of uncertainty using the bootstrap approach, it is more challenging to evaluate the second source of uncertainty. In addition to the hyperbolic yield response function used in this study, we also tested the quadratic plateau function, using two different methods (i.e., with and without considering the fertilizer-to-crop price ratio; see details in Text S6 and S7 in SI). The use of quadratic plateau function resulted in higher N inputs projection than hyperbolic yield response function (see SI Table S4 and Figure S10). It leads to even larger difference between the "Same TMP" and "Same NUE" approaches, supporting our conclusions regarding the impacts of considering diminishing returns on N input projection based on the hyperbolic yield response function. We focus on reporting and discussing the results from the hyperbolic yield response function in the main text, because this function has been implemented on national scale before, and the projected values are comparable to those in the existing literatures.

A survey of existing projections for crop N inputs reveals large variations among studies (Figure 6), 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 S5). Among all studies, Mogollón et al. (2018) and Lassaletta et al. (2016) 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. (2018) projected M based on the relationship between M and Gross Domestic Product (GDP) 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. (2016) 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, Henao, & Rosegrant (2004) and Erisman, Sutton, Galloway, Klimont, & Winiwarter (2008), assume an increase in NUE by 50% and 30% by 2050 relative to the baseline (1997 and 1995–97) resulting in 100 and 107 Tg N yr^{-1} N fertilizer inputs for cropland, respectively. Despite using different approaches, their projections estimates are quite 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. (2003) and Wood, Henao, & Rosegrant (2004) assumed constant NUE in their projection, but Cassman et al. (2003) 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. (2003) and 6% lower than Wood, Henao, & Rosegrant (2004). 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.

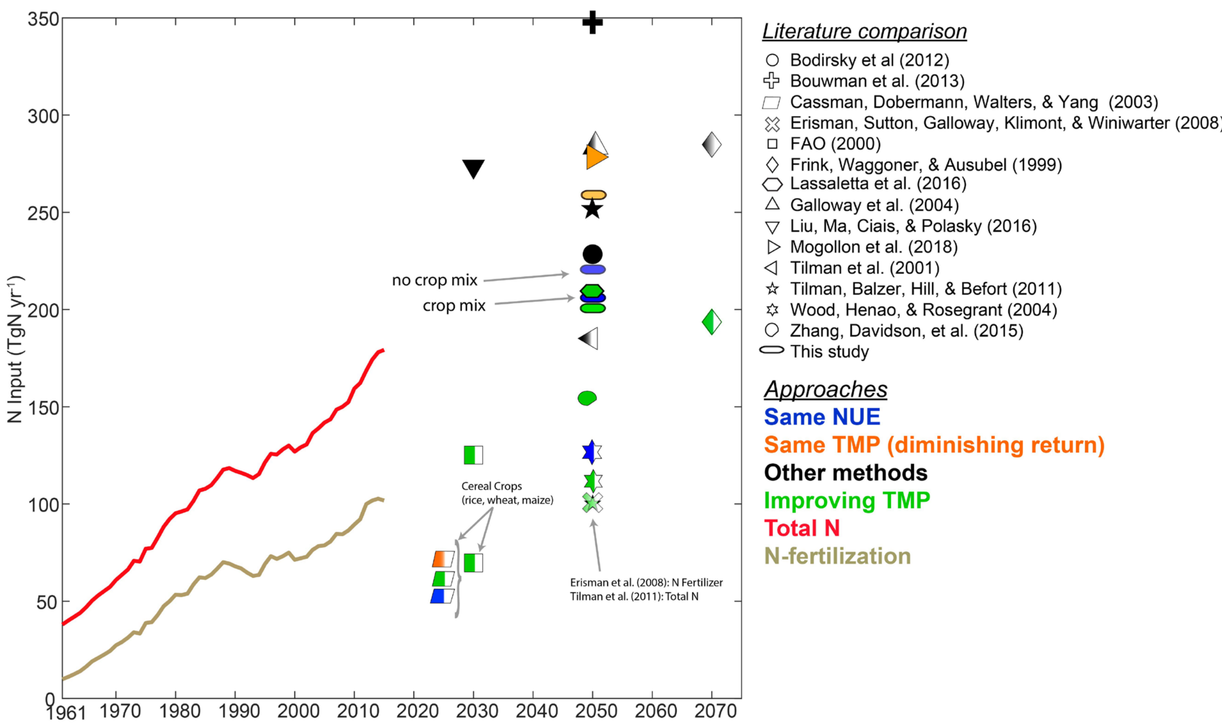

Figure 6: Projections of N input from different studies along with the projection estimates from this study. Each symbol shows different studies, while their fill color shows the estimates corresponding to the approaches. If a symbol is filled entirely (half-filled), then the projections are for total N (N fertilizer), respectively. Projections only for cereal crops are indicated by arrows, while estimates which include all crop classes are not. The details of the projections from these studies are in SI Table S5.

Implications for crop N management

Crop N management is facing tremendous challenges in the next three decades. The projections in this study suggests that N inputs will continue to increase by 59 Tg N yr^{-1} (N surplus and N fertilizer inputs will reach 103 and 115 Tg N yr^{-1} respectively , and NUE will be 0.49) 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, Davidson, et al. (2015) 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). 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 types 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 Europe (EU) have managed to increase their NUE from 44% in 1980s to 62% in 2010s while maintaining yield through adopting TMP such as '4Rs' principles (i.e., right source, right time, right place and right rate for fertilizer application (International Fertilizer Association (IFA), 2009) and improved crop cultivars (Ferguson, 2015). However, such improvement has been heavily relying on market incentives in the USA and strong regulations at EU, and it is not clear whether those mechanisms will continue to be as effective in the next few decades given the volatile crop and energy markets. In contrast to these developed countries, SSA countries are still at the early intensification stage, with low N inputs and high NUE. With projected increase in crop production by 60–110% by 2050 (Foley et al., 2011; Hunter et al., 2017; Tilman et al., 2011), more N inputs and lower NUE are expected based on the development trajectories exhibited by most developed and developing countries around the world (Zhang, Davidson, et al., 2015). Changing such trajectories for crop intensification in SSA (in other words, achieving the production increase without reducing NUE) would require yield increase relying more on TMP improvement than input increase, which is challenging for those least developed countries with very limited resources (Kanter, Bartolini, et al., 2020; Sutton et al., 2013). 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. The heavily subsidized fertilizer provides limited incentives for farmers to adopt more N-efficient TMP, while phasing out the subsidies need to be balanced with the food security concerns and social well-being of the 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 both affect yield response to N inputs. For example, increasing heat stress caused by global warming might stagnate the yield of major cereal crops (maize, soybean, wheat, and rice) even after implementing management practices (Iizumi et al., 2017; Lobell & Gourdji, 2012; Rosenzweig et al., 2014). 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, including but not limited to split-application, soil testing, smart sensors, slow released fertilizer, and conservation tillage. Many of these TMP are associated with low or even zero 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 (Compton, Leach, Castner, & Galloway, 2017), and consequently, an increasing number of countries have put forward policies and targets to curtail N inputs in agricultural production. For example, the Chinese government set the goal of "Zero growth" of fertilizer consumption in 2015 (Ju, Gu, Wu, & Galloway, 2016), the Vietnamese government in 2012 released a plan to adopt high-tech solutions in collaboration with R&D for improved agricultural technologies until 2020 (Kanter, Chodos, Nordland, Rutigliano, & Winiwarter, 2020), and the Egyptian government released a Biodiversity Strategy and Action Plan for conservation that proposed limiting fertilizer input (Kanter, Chodos, et al., 2020). 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 conventional approach for projecting NUE under the Business-As-Usual (BAU) scenario usually assumes NUE that stays at the current level, and this assumption results in a much lower projection in N inputs than the projection considers the diminishing return of yield to N inputs under the same Technologies and Management Practices (TMP). The optimistic projection by the conventional 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 the BAU scenario, 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.

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