Understanding and reconciling different approaches for quantifying nitrogen use efficiency in cropping systems

Zhi Quan
Institute of Applied Ecology, Chinese Academy of Sciences https://orcid.org/0000-0003-4918-7382
Xin Zhang (xin.zhang@umces.edu)
University of Maryland Center For Environmental Sciences https://orcid.org/0000-0003-1619-1537
Yunting Fang
Institute of Applied Ecology, Chinese Academy of Sciences https://orcid.org/0000-0001-7531-546X
Eric Davidson
University of Maryland Center for Environmental Science https://orcid.org/0000-0002-8525-8697

Article

Keywords: nitrogen use efficiency (NUE), difference method, 15N tracer method, N balance method, soil legacy effect, replenishment effect

Posted Date: August 27th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-60369/v1

Version of Record: A version of this preprint was published at Nature Food on April 21st, 2021. See the published version at https://doi.org/10.1038/s43016-021-00263-3.

Abstract

Nitrogen use efficiency (NUE) has been widely used in cropping systems to study nitrogen (N) cycles and inform N management on various spatial scales, from a single plant to the globe. Although the number of NUE studies is growing, interpretation of results is unfortunately hindered by widely differing definitions and quantification methods among studies, suggesting a pressing need for harmonization of approaches. Here, we proposed a conceptual framework to understanding the differences and connections among three major approaches for determining NUE, namely, the difference approach, 15N tracer approach, and N balance approach. Using the Chinese cereal cropping system as an example, we demonstrated that the results of those NUE assessments could be very different even for the same cropping system (0.32, 0.24, and 0.52, respectively). Such a difference is attributable largely to the soil legacy effect and could be reduced by extending the observations for a longer term. This study provides the necessary understanding to reconcile NUE values from different approaches and consequently to better inform N management in cropping systems.

Introduction

Nitrogen (N) is a critical element for boosting crop yield and is consequently important for global food security[1]. However, large N inputs to croplands as fertilizer and manure lead to N losses to the environment via leaching or gaseous emissions, leading to increased adverse environmental impacts from local to global scales (e.g., eutrophication and climate change) and threatening human health[2]. To address these challenges, the efficient management of N in crop production is essential[3].

To measure the efficiency of N use in crop production and determine the impacts of N inputs on the environment, an indicator of nitrogen use efficiency (NUE) is widely and increasingly used by agronomists, biogeochemists, policymakers, and other stakeholders at various temporal and spatial scales[4]. Unfortunately, while the use of NUE is growing, interpretation and synthesis of results is impeded by widely differing definitions and calculation methods, hindering comparisons among studies and experience-sharing among researchers and regions[5]. Understanding the differences and connections among existing approaches for quantifying NUE is particularly important and timely due to the growing policy interest in evaluating the agricultural sustainability[6]. Many international organizations (e.g., Sustainable Development Solution Network, United Nations Environmental Program, Global Partnership on Nutrient Management, European Union N Expert Panel) and countries (e.g., Germany) have attempted to use NUE or develop indicators based on NUE to assess the sustainability of nutrient management. However, debates about the methodologies remain, urging for a better understanding of the NUE concepts and the approaches for quantifying it.

There have been three main approaches widely used for defining and quantifying NUE (Table 1 and Fig. 1):

- The difference approach (NUE_{diff}), defined as the harvested N in fertilized plots minus the harvested N in nonfertilized control plots, then divided by N fertilizer inputs;
- The ^{15}N tracer approach (NUE_{15N}), which applies fertilizer with ^{15}N tracer and tracks the proportion of ^{15}N harvested in the crop product;
- The N balance approach (NUE_{bala}), defined as the harvested N divided by all N inputs.

A review of the existing literature suggests that the NUE of cereal cropping systems was in the range of 0.27–0.37 (China) and 0.42–0.48 (the globe) based on the NUE_{diff} and NUE_{15N} approaches, while they were approximately 0.68 (China) and 0.62–0.99 (the globe) based on the NUE_{bala} approach (Table 1). These contrasting results depict a very different picture of crop N management in China and around the world, leading to confusion or even misinformed decisions in N management practices and policies. Such confusion may also exist on a plot scale. For example, in some well-managed field trials, the observed NUE_{diff} or NUE_{15N} are usually around 0.2–0.5, appearing to indicate high N-loss risk and significant room for NUE improvement[8, 10, 16]; however in those trials, large N harvests were usually observed (close to or even higher than N input), and NUE based on N balance approach could be close to or even higher than one, indicating very low N-loss risk or even depletion of soil N stock.

Here, we proposed a conceptual framework, with supporting case studies, to identify the differences and connections among these three commonly used approaches for defining and quantifying NUE and to discuss major considerations for choosing proper approaches as the use of NUE assessments grows.

Main Text

The same principle but different approaches

In principle, NUEs are defined and quantified to assess how much of the N input to a system is used effectively by the product and harvested from the system[5]. In practice, three major approaches developed under different experimental and operational settings can lead to divergent results and possibly differing interpretations, even for the same experimental site and for the same growing season (Fig. 1a, b, c). A conceptual framework that depicts the linkages and differences among the three approaches is visualized in Fig 1d. While all three approaches share harvested N (HN_T) and N fertilizer inputs (F_N) as part of their calculation formulas, the relationship among NUEs obtained with these approaches can be determined by harvested N in the control plots (HN_C), fraction of harvested N derived from in-season-applied N fertilizer (%Ndff), and nonfertilizer N inputs (NF_N) measured in NUE_{diff}, NUE_{15N}, and NUE_{bala} approaches respectively. Mainly due to legacy effects of previous years' fertilizer additions, points B and C in Fig. 1d (determined by HN_C and %Ndff respectively) are usually above reference point A (determined by NF_N), suggesting a higher NUE_{bala} than that obtained with the other two approaches. Such differences are prevalent, especially in short-term experiments (e.g., experiments for one or several growing seasons).

To showcase the differences among approaches, we constructed an example for China's cereal cropping system based on the synthesis of values from the literature (numbers in the brackets of Fig. 1d). We developed this example based on mean values from the literature (mainly obtained by national on-farm surveys and field trials) instead of a single experiment because few studies have tested all three approaches simultaneously, and experiments for a single site may lack representativeness. The results suggest that even for the same cropping system (i.e., Chinese cereal cropping system in this case) with consistently defined N inputs and harvest rates, different NUE approaches will result in different values with the following trend: NUE_{15N} (0.24) < NUE_{diff} (0.32) < NUE_{bala} (0.52). Consequently, it is critical to understand the causes for the differences among those approaches to better achieve efficient N management.

Mind the gap: differences and connections among the three approaches

The most obvious difference among the three approaches is that NUE_{diff} and NUE_{15N} assess the efficiency of fertilizer use, while NUE_{bala} assesses the efficiency of N inputs beyond fertilizer (F_N + NF_N). However, when the bioavailability of NF_N (BA_{NF}, long-term uptake% of NF_N) is the same as that of F_N (BA_F), then the NUE for F_N use based on the balance approach (NUE_{bala_F}, = (HN_T – NF_N × BA_{NF})/F_N) is the same as NUE_{bala} (Supplementary Fig. 1). It is possible that BA_{NF} is higher than BA_F, but even if all of NF_N can be converted to crop product during the same growing season (i.e., BA_{NF} = 1.0), the adjusted NUE for fertilizer use based on the N balance approach could still be lower than NUE_{diff} and NUE_{15N}[14]. Taking our Chinese cereal cropping system case as an example, NUE_{bala_F} ranges from 0.38 to 0.66, depending on the bioavailability of NF_N (Supplementary Fig. 1). However, even the lower boundary of NUE_{bala_F} is still higher than NUE_{15N} (0.24) and NUE_{diff} (0.32), indicating other important drivers for the differences between NUE_{bala} and the other two approaches.

The major driver for the remaining differences between NUE_{bala} and the other two approaches is the legacy effect of fertilization during previous seasons (Table 1). Fertilizer N inputs not only supply the plant N needs for the season of application but also replenish soil N and support the maintenance of the long-term N supply in the soil[10]. For example, the meta-analysis of Yan et al.[14] shows that only 42% of N fertilizer is recovered by crop products during the same growing season, while 34% is retained in the soil, which could be utilized in future growing seasons or lost to the environment.

With the exception of newly formed croplands, most farms have a history of fertilizer or manure amendments. This commonplace legacy or replenishment effect of fertilizer application indicates that a long-term view of fertilizer efficiency is necessary in most cases for understanding the NUE_{diff} and NUE_{15N} approaches (Supplementary Fig. 2). However, often due to logistical constraints (e.g., funding and site maintenance), the experiments for determining NUE are usually conducted for one to several growing seasons with different considerations of legacy effects, leading to divergence in the results. With single-season observations, the NUE_{diff} and NUE_{15N} approaches reflect the fertilizer recovery rate during the current growing season, with no or largely discounted consideration of legacy effects. In contrast, the NUE_{bala} is based on the assumption of mass balance in soil N stocks, and does not exclude the long-term legacy effects of N inputs but may over- or underestimate the actual NUE if significant mining or accumulation of soil N occurs during the year of observation (Table 1). Therefore, the difference between single-season NUE_{15N} and NUE_{bala} (e.g., the difference between 0.52 and 0.24 in the Chinese cereal cropping system case) can be used to estimate the size of the legacy effect of applying ^{15}N fertilizer (Fig. 1d).

If the observation period could be extended from a single season to multiple years or even decades, the assessment outcomes from the three approaches will change due to the diminishing legacy effect: the HN_C will likely decrease as soil N stock is continuously depleted without replenishment from additional N inputs, while the cumulative %Ndff will likely increase as more ^{15}N will be recovered since the pulse addition of ^{15}N tracer (i.e., points B and C will likely to move towards point A in Fig. 1d). Consequently, the observed NUE_{diff} and the cumulative NUE_{15N} will likely increase as observation is conducted for a longer period of time (Fig. 1e). Moreover, the NUE_{bala} may fluctuate due to the year-to-year yield variation, but the moving averages of the NUE_{bala} over several years under consistent management practices tend to be stable, as the average annual soil N stock change tends to be negligible compared to the annual N fertilizer inputs over a long period of time[17]. Consequently, the assessments from the NUE_{15N} and NUE_{diff} approaches tend to converge with that from the NUE_{bala} approach for long-term observations (Fig. 1e).

The difference between the NUE_{diff} and NUE_{15N} assessments could be attributed to the following reasons: 1) In addition to directly providing N for plant uptake, fertilizer inputs may change the in-season soil N supply by promoting root-mediated or soil microbe-mediated soil N turnover or abiotic adsorption-desorption exchange, leading to the differences between NUE_{diff} and NUE_{15N}[13, 14, 18]. This effect tends to increase the harvested N in the fertilized plots of the NUE_{diff} approach but does not increase the recovered fertilizer N in the NUE_{15N} approach. Consequently, it may lead to a higher NUE value for the NUE_{diff} approach. 2) Given the “law of diminishing returns” between N inputs and N yields, the NUE for F_N is inherently lower than the NUE for NF_N (slope of line DB < slope of line BO in Fig. 1d). Consequently, NUE_{diff}, which is based on the different yield responses to two N input levels, could show a lower NUE result than the approaches dealing with only one N input (i.e., NUE_{bala} or NUE_{15N}). Overall, NUE_{diff} can be higher or lower than NUE_{15N}, depending on which reason dominates, but the difference is generally low in most reports (e.g., < 0.1 in Table 1).

Choosing a proper approach

Overall, when the observation is conducted over a long term and the NF_N is negligible, the three approaches for NUE assessment (NUE_{diff}, NUE_{15N}, and NUE_{bala}) tend to converge and the assessments from these approaches could be compared for informing management practices. However, in practice, these approaches are often implemented for only one or a few growing seasons due to many logistical constraints, and the NF_N sources are usually diverse and their quantities are uncertain. Therefore, the comparison of NUE assessments from different approaches may be biased by the inherent differences associated with these approaches, and it is essential that the assessment approach is carefully chosen and consistently implemented among practices or regions to avoid such bias.

Fortunately, a proper approach can be chosen by identifying the goal of the assessment and comparison, as well as the associated logistical requirements, including cost. For example, NUE_{diff} is a straightforward and cost-effective approach to assess the short-term response of harvested N to N fertilization under different environments or management conditions. The NUE_{diff} approach is suitable for experimental situations, such as research stations, but it is often difficult to perform in an actual farming operation because it is hard to convince farmers to devote some portion of their land to low yields due to lack of N fertilization. NUE_{15N} is most accurate in tracing the fate and distribution of N fertilizer in the soil-crop system, but it is usually applicable at relatively small space-time scales due to the high cost of ^{15}N-materials and ^{15}N-measurements.

In comparison, NUE_{bala} has great advantages in evaluating the resource and environmental performances of N inputs in crop production, especially when the averaged change in soil N stock is small or even negligible compared to the annual N inputs during the observation period. 1) Given the definition of NUE_{bala} and soil N balance, “1–NUE_{bala}” can be considered the fraction of N lost or subject to lose to the environment[11]. Applying a similar formula to NUE_{diff} and NUE_{15N}, N losses to the environment are potentially overestimated due to the legacy effect (description of such overestimation existed widely in published papers[12, 13, 19]). 2) NUE_{bala} is based on data more readily available from farm to national scales. For example, grain yield and N fertilizer rates are typical values used in farmers’ bookkeeping, and they are commonly collected in national or regional surveys or statistics. Admittedly, the data for some NF_N sources (e.g., biological N fixation) are still not widely available, and using default values may introduce uncertainties. Such uncertainties could be important to consider when the NF_N is not negligible (e.g., > 5%) compared to the fertilizer N rate.

It should be noted that, despite the approach, short-term observations are limited in reflecting the long-term effect of changing management practices[15]. First, crop yield and N uptake vary from year to year due to changing weather conditions and consequently affect the NUE assessment. Second, the impact of the new management practices on yield and NUE may be buffered by a soil legacy effect. Agronomic measures combined with fertilizer rate reduction are often reported in the literature as being effective for improving in-season NUE_{diff} or NUE_{15N} while maintaining crop yields[20]. However, it must be recognized that some of these measures may only improve the soil environment and promote the release of previously accumulated nutrients in the short term and may eventually deplete soil N supply capacity, as well as yield and NUE, in the long term. Accounting for N balance and NUE_{bala} may help to relieve part of the concerns about soil depletion, but NUE_{bala} assessment tends to be biased when the soil N stocks are not in a steady state (Table 1). Consequently, to assess the impacts of different management practices on NUE, we recommend long-term observations (e.g., over a decade, but at least beyond three growing seasons) when possible.

Conclusion

The three commonly used NUE assessment approaches, NUE_{diff}, NUE_{15N}, and NUE_{bala}, are all designed to assess the effectiveness of N inputs to a crop production system. However, the different experimental designs, along with nonfertilizer N inputs and soil legacy effects, lead to differences in the assessment results even for the same crop production system. Improved understanding of the advantages and disadvantages of each approach is needed as studies of NUE increase, because it is critical to choose a proper approach based on the major goal of assessment and implement it consistently to enable fair comparisons. Given the limitations of the short-term observations and soil legacy effect, it is important to implement long-term trials for assessing the impacts of management practices on yield and the efficiency of N use.

Methods

Average N inputs and N harvests in the Chinese cereal cropping system. The average synthetic fertilizer N input was 208 kg N ha^{-1} $season^{-1}$ based on the on-farm investigation at the national scale during 2005–2014[21-23] (Supplementary Table 2). The nonfertilizer N input was 59 kg N ha^{-1} $season^{-1}$ based on the on-farm survey for manure application[23] (16 kg N ha^{-1} $season^{-1}$, Supplementary Table 2) and the model simulation for deposition (17 kg N ha^{-1} $season^{-1}$), biological fixation (20 kg N ha^{-1} $season^{-1}$), irrigation (4 kg N ha^{-1} $season^{-1}$), and seeds (2 kg N ha^{-1} $season^{-1}$)[24].

The average harvest N (HN_T, aboveground N uptake = grain + straw) was 138 kg N ha^{-1} $season^{-1}$, which was calculated according to the grain yield (on-farm investigation at the national scale during 2005–2014), the average weighted ratio of “grain: straw” (or harvest index), and average N concentrations in grain and straw in Chinese cereal crops[21-23] (Supplementary Table 2). In the simulation, all straw was assumed to be harvested and regarded as a product, regardless of how it was used after removal from field boundaries.

NUE calculations for the Chinese cereal cropping system. We estimated the HN_C according to the average reductions in grain yield and N concentration according to published results for Chinese cereal cropping systems. In this simulation, the control was estimated to have only 72.5% of the yield (Supplementary

Fig. 3) and 71.0% of the N concentration (Supplementary Table 2) of the treatment with conventional N fertilization, so the aboveground N uptake in the control was only 51.4% (= 72.5% × 71.0%) of that in the treatment. This proportion (HN_C%, = HN_C/HN_T) was in line with that for cereal cropping systems at the global scale[14]. Consequently, the HN_C was calculated as 138 × 0.514 = 71 kg N ha^{-1} season^{-1}.

In previous *in situ* ^{15}N tracer studies, the Ndff% was generally determined. Under the condition of conventional N fertilization (fertilizer N rate in the range of 100–300 kg N ha^{-1} season^{-1}), the Ndff% in the application year was in the range of 0.115–0.696 (n=216) with an average of 0.358 (Supplementary Table 1). As a result, the ^{15}N recovered by harvest during the application season was calculated as 138 × 0.358 = 50 kg N ha^{-1} season^{-1}.

The average NUE_{bala} in the Chinese cereal cropping system was calculated directly according to the fluxes of N inputs and HN_T. In China, the agricultural sector of the government conducted several national soil censuses in different years. The results showed that the N reserves in Chinese cropland have only changed slightly (averagely increasing approximately 3 kg N ha^{-1} yr^{-1}, or 0.18% yr^{-1}) since 1980, which indirectly indicates that soil N is almost in a steady state[17].

Simulating NUE_{diff}, NUE_{15N}, and NUE_{bala} changes in long-term experiments. The data sources for NUE, such as N fertilizer inputs and N harvests, were from the Rothamsted Broadbalk Wheat Experiment from 1969, when high yielding short straw wheat varieties and 3- and 5-course rotations were introduced and modern insect, weed and disease control began (www.era.rothamsted.ac.uk/). The harvested N values for the 1st wheat in treatments receiving normal rates of phosphorus, potassium, and magnesium fertilizer but receiving 0 and 144 kg ha^{-1} N fertilizer (treatment code: N0PKMg and N3PKMg) were selected as HN_C and HN_T in this simulation. To calculate NUE_{bala}, the nonfertilizer N input was estimated as the sum of the annual wet deposition record[25] and a uniform estimate was used for other N inputs (15 kg N ha^{-1} yr^{-1} including biotic N fixation, seed, etc.). The experiment started in 1843 and has lasted for > 170 years, which means that the soil in the control plots (receiving 0 kg fertilizer-N ha^{-1}) had a lower total N content than that in the treatment plots in 1969 due to the lower N fertilizer and residual N inputs. Therefore, we expect the differences between NUE_{bala} and NUE_{diff} to be underestimated at the beginning of the study period (1969–2015).

Since there was no long-term ^{15}N experiment at the same site for direct comparison with the NUE_{diff} and NUE_{bala} approaches, we constructed a possible NUE_{15N} observation record using the following assumptions: 1) ^{15}N labeled fertilizer was applied in 1969 at the rate of 144 kg N ha^{-1}, and the same rate of nonlabeled fertilizer was applied in the subsequent years; 2) the proportions of ^{15}N harvested (%Ndff) in the first season and in subsequent seasons were the same as those in a 28-year-long ^{15}N tracer experiment in France[26]. Microplot-based ^{15}N tracer trials were only conducted for four consecutive years

(1980-1983) in the “N3PKMg” plots receiving 144 kg ha^{-1} N fertilizer. The %Ndff of winter wheat in the first season was in the range of 0.518–0.648 with an average of 0.584[27]. This percentage was very close to that in Sebilo et al.[26] where the %Ndff in the first season equaled 0.581. We predicted the potential %Ndff after 28 years using a two-pool decay model (Supplementary Fig. 4). The original data for making Fig. 1e can be found in Supplementary Table 4.

Declarations

Acknowledgments

We thank Dr. Margaret Glendining from the Rothamsted Research for providing us with the data to indicate the changes of NUE in the long-term Broadbalk Wheat Experiment.

Competing interests

The authors declare no competing interests.

References

1. Houlton, B. Z., et al. A world of cobenefits: Solving the global nitrogen challenge. *Earth's future* **7**, 865–872 (2019).
2. Erisman, J. W. et al. *Nitrogen: Too much of a vital resourc Science Brief*. (WWF Netherlands, Zeist, The Netherlands, 2015). http://www.louisbolk.org/downloads/3005.pdf
3. Zhang, X. et al. Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
4. Norton, R., Davidson, E. A. & Roberts, T. *Position paper: Nitrogen use efficiency and nutrient performance indicators*. (Global Partnership on Nutrient Management, Washington DC, 2014). http://wedocs.unep.org/handle/20.500.11822/10750
5. Zhang, X. et al. Centennial Grand Challenge: Quantifying nutrient budgets for sustainable nutrient management. *Global Biogeochemical Cycles*, **34**, e2018GB006060. (2020).
6. European Union Nitrogen Expert Panel. Nitrogen use efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems (Wageningen University, Wageningen, 2015). http://wedocs.unep.org/handle/20.500.11822/12087
7. Jin, J. Changes in the efficiency of fertiliser use in China. *Journal of the Science of Food and Agriculture* **92**, 1006–1009 (2012).
8. Zhang, F. et al. Nutrient use efficiencies of major cereal crops in china and measures for improvement. *Acta Pedologica Sinica* **45**, 915–924 (2008). (in Chinese with English abstract)
9. Yu, F. & Shi, W. Nitrogen use efficiencies of major grain crops in China in recent 10 years. *Acta Pedologica Sinica* **52**, 1311–1324 (2015). (in Chinese with English abstract)

10. Ju, X. & Christie, P. Calculation of theoretical nitrogen rate for simple nitrogen recommendations in intensive cropping systems: A case study on the North China Plain. F*ield Crops Research* **124**, 450–458 (2011).
11. Zhang, C., Ju, X., Powlson, D., Oenema, O. & Smith, P. Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. *Environmental Science and Technology* **53**, 6678–6687 (2019).
12. Raun, R. & Johnson, G. V. Improving nitrogen use efficiency for cereal production. *Agronomy Journal* **91**, 357–363 (1999).
13. Krupnik, T. J., Six, J., Ladha, J. K., Paine, M. J. & van Kessel, C. *An assessment of fertilizer nitrogen recovery efficiency by grain crops* (Island Press, 2004).
14. Yan, M., Pan, G., Lavallee, J. M. & Conant, R. T. Rethinking sources of nitrogen to cereal crops. *Global Change Biology* **26**, 191–199 (2020).
15. Smith, C. J. & Chalk, P. M. The residual value of fertiliser N in crop sequences: An appraisal of 60 years of research using ^{15}N tracer. *Field Crops Research* **217**, 66–74 (2018).
16. Quan, Z., et al. Fertilizer nitrogen use efficiency and fates in maize cropping systems across China: Field ^{15}N tracer studies. *Soil and Tillage Research*, 197, 104498 (2020).
17. Yan, X., et al. Fertilizer nitrogen recovery efficiencies in crop production systems of China with and without consideration of the residual effect of nitrogen. *Environmental Research Letters* **9**, 095002 (2014).
18. Liu, X. A., van Groenigen, K. J., Dijkstra, P. & Hungate, B. A. Increased plant uptake of native soil nitrogen following fertilizer addition - not a priming effect? *Applied Soil Ecology* **114**, 105–110 (2017).
19. Cassman, K. G., Dobermann, A. & Walters, D. T. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* **31**, 132–140 (2002).
20. Chen, P. et al. Effects of reduced nitrogen inputs on crop yield and nitrogen use efficiency in a long term maize-soybean relay strip intercropping system. *PLoS ONE* **12**, e0184503 (2017).
21. Chen, X. et al. Producing more grain with lower environmental costs. *Nature* 514, 486–489 (2014).
22. Cui, Z. et al. Pursuing sustainable productivity with millions of smallholder farmers. *Nature* **555**, 363–366 (2018).
23. Zhang, W. et al. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 8375–8380 (2013).
24. Gu, B., Ju, X., Chang, J., Ge, Y. & Vitousek, P. Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 8792–8797 (2015).
25. Storkey, J. et al. Grassland biodiversity bounces back from long-term nitrogen addition. *Nature* **528**, 401–404 (2015).

26. Sebilo, M., Mayer, B., Nicolardot, B., Pinay, G. & Mariotti, A. Long-term fate of nitrate fertilizer in agricultural soils. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 18185–18189 (2013).
27. Powlson, D.S. et al. The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment. *Journal of Agricultural Science, Cambridge* **107**, 591–609 (1986).

Tables

Table 1. Definition, calculation, and mean values of nitrogen use efficiency (NUE) in cereal cropping systems based on three major approaches.

Approaches	Difference approach (NUE_{diff})	^{15}N tracer approach (NUE_{15N})	N balance approach (NUE_{bala})
Major focus of the assessment	The use efficiency of N fertilizer	The use efficiency of N fertilizer	The use efficiency of all N inputs, and the fraction of N inputs subject to surplus or loss
Application on spatial scales	Plot, field	Confined microplate, plot, field	Field, watershed, region, nation, or globe
Application on temporal scales	Single to multiple growing seasons	Often conducted for a single growing season	From a single growing season to multiple decades
Requirement for soil N status	No requirement	No requirement	Change in soil N stock is low or negligible compared to total N input and total N output
Soil legacy effect	Largely excluded for short-term experiments	Not considered for single-season experiments	Partly or all included based on soil N status*
Formulas#	$= (HN_T – HN_C)/F_N$	$= (HN_T – Ndfs)/F_N$ $= (HN_T \times \%Ndff)/F_N$	$= HN_T/(F_N + NF_N)$
Assumption about the contribution of N inputs to harvested N	The contribution of other N inputs (e.g. NF_N) to harvested N during the studied period is the same (= HN_C) in the control and treatment plots	The contribution of other N inputs (e.g. NF_N) to harvested N during the studied period can be traced as Ndfs (HN_T - Ndff)	The contribution of all N inputs to harvested N during the studied period is HN_T
Data source	Mostly field trials	Mostly field trials	Mostly statistical data or survey data
Mean values in China	**0.30**[7]; **0.27** (n=667)[8]; **0.35** (n=461)[9]	**0.37** (n=92)[10]; **0.36** (n=216) (Supplementary Table 1)	**0.68**[†‡, 3]; **0.68**[†, 11]
Mean values at global scale	**0.48**[†, 12]; **0.47** (n=748)[13]; **0.48** (n=452)[14]	**0.44** (n=804)[13]; **0.42** (n=622)[14]; **0.42** (n=88)[15]	**0.99**[†‡, 3]; **0.62**[†, 4]

* Only when the soil N status is in a steady state can the soil legacy effect of N input in the current season (to subsequent seasons) be offset by the soil legacy effect of N input in the previous seasons (to the current season).

Abbreviations: fertilizer N inputs (F_N), nonfertilizer N inputs (NF_N; including deposition, manure, biological fixation, irrigation, seeds, etc.), harvested N in the control plots (HN_C, without N fertilization), harvested N in the treatment plots (HN_T, with N fertilization), fraction of harvested N derived from in-season-applied N fertilizer (%Ndff), harvest N derived from soil (Ndfs, = HN_T – Ndff).

† To facilitate the comparison between different approaches, all aboveground N was uniformly calculated as the harvested N. For cereal crops, the NUE for aboveground N (grain + aboveground straw) is approximately 1.45 times the NUE for grain N according to their empirical ratio.

‡ Neither biological N fixation nor manure applications were considered.

Figures

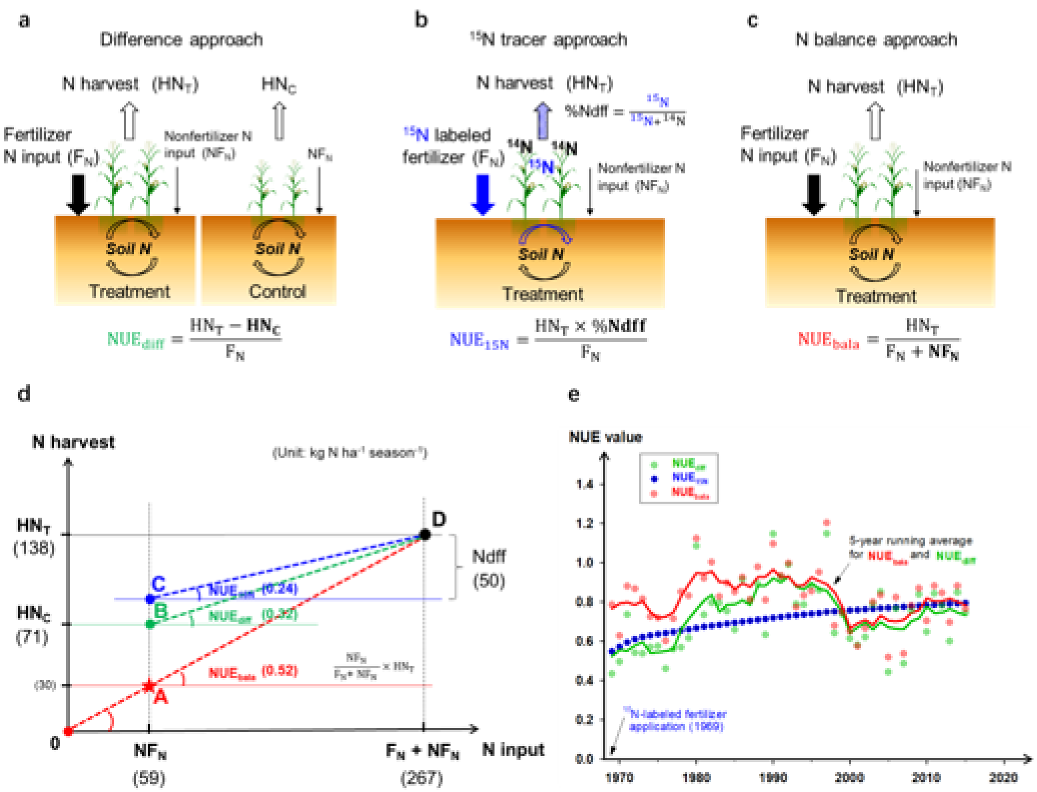

Figure 1

Differences and connections among three major approaches for determining NUE. a,b,c, Schematic representation of experimental settings and calculation methods for NUE using three different approaches. See Table 1 for definitions of abbreviations. d, The definition of NUEdiff, NUE15N, and NUEbala under the same observation framework. Number in brackets are national averages for the Chinese cereal cropping system. e, An example of NUEdiff, NUE15N (simulated), and NUEbala changes in the long-term Rothamsted Broadbalk winter wheat experiment, United Kingdom.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationNF6.docx