



Different quantification approaches for nitrogen use efficiency lead to divergent estimates with varying advantages

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Nitrogen use efficiency (NUE) is a key indicator with which to study nitrogen cycles and inform nitrogen management. However, different quantification approaches may result in substantially divergent NUE values even for the same production system or for the same experimental plot. Based on our investigation of the differences between and connections among the three principal approaches for NUE quantification, we offer recommendations for choosing the appropriate approach and call for long-term observations to assess the impacts of management practices.

Nitrogen is a critical element for boosting crop yield and thereby ensuring global food security¹. However, large nitrogen inputs to croplands as fertilizer and manure lead to nitrogen losses to the environment via leaching or gaseous emissions, resulting in increased adverse environmental impacts from local to global scales and threatening human health². To measure the efficiency and potential environmental impacts of nitrogen use in crop production, indicators of nitrogen use efficiency (NUE) are widely and increasingly used by agronomists, environmental scientists, biogeochemists, policymakers and other stakeholders at various temporal and spatial scales^{3,4}. Recently, this indicator has been adopted by many international organizations (Supplementary Note 1) to guide improvement in nitrogen management and food system sustainability given overfertilization in some regions and insufficient fertilizer inputs in others. However, the wide application of the NUE indicator is accompanied by differing definitions and quantification methods (Supplementary Table 1), potentially leading to misinterpretation or confusion by stakeholders and hindering comparisons among studies and experience sharing among researchers and regions^{3–6}.

The principal approaches for defining and quantifying NUE include nitrogen difference (NUE_{diff}), ^{15}N tracer (NUE_{15N}) and nitrogen balance (NUE_{bala}) (Fig. 1). Applying these approaches to assess the cereal cropping system in China, a review of the existing literature suggests that NUE_{diff} and NUE_{15N} values range between 0.27 and 0.37, while NUE_{bala} is around 0.68 (Table 1), depicting a very different picture of crop nitrogen management in China to different stakeholders. While the former assessments, often used by agronomic and biogeochemistry researchers, indicate high nitrogen-loss risk and substantial room for NUE improvement^{7–10}; the latter, often used by policymakers and farmers, indicates much lower nitrogen-loss risk¹¹. Therefore, understanding and reconciling the differences among the various approaches for quantifying NUE is urgently needed to bridge the communication gaps among

stakeholders, and to better inform decisions on the choice of NUE quantification approach, as well as nitrogen management practices and policies (Table 1)^{3–6}.

Mind the gap: differences and connections among the three approaches

In this paper we propose a conceptual framework to depict the linkages and differences among the three major approaches for NUE quantification (Fig. 2a). In principle, all three approaches are designed to assess how much of the nitrogen input to a system is removed from the system as crop products; but in practice, they have different experimental and operational settings and potentially lead to divergent results (Table 1). For an experimental plot or production system operating at a certain level of nitrogen fertilizer input (F_N) and harvested nitrogen (HN_c ; that is, point D in Fig. 2a), NUE_{bala} , NUE_{diff} and NUE_{15N} correspond to the slopes of lines BD, CD and OD (or AD), respectively, which are determined by additional variables measured by each approach: the harvested nitrogen in the control plots (HN_c) by NUE_{diff} , the fraction of harvested nitrogen derived from in-season-applied nitrogen fertilizer (%Ndff) by NUE_{15N} , or the non-fertilizer nitrogen inputs (NF_N) measured by NUE_{bala} . Depending on the observed values for these variables, the NUEs assessed by the three approaches are not necessarily the same even for the same experimental plot or production system, and NUE_{bala} is often observed to be much higher than NUE_{diff} and NUE_{15N} (that is, points B and C are often above point A). Following the conceptual framework in Fig. 2a, we constructed an example for China's cereal cropping system by synthesizing values from the literature (numbers in parentheses in Fig. 2a; Supplementary Note 2). This example shows the following relation: $NUE_{15N} \approx NUE_{diff} < NUE_{bala}$ (Fig. 2a). The same relation has also been found for each of the three major cereal crops within China's cereal cropping system (that is, maize, wheat and rice; Extended Data Fig. 1).

The most obvious difference between the three approaches is that NUE_{diff} and NUE_{15N} assess the efficiency of fertilizer use whereas NUE_{bala} assesses the efficiency of nitrogen inputs beyond fertilizer ($F_N + NF_N$). However, this difference is probably not the major cause for the different NUE assessment values for the same production system, because most croplands either have negligible NF_N compared with F_N (for example, in most intensively cultivated croplands), or have similar efficiencies for F_N and NF_N (therefore NUE_{bala} is a proxy for the fertilizer efficiency). Even when

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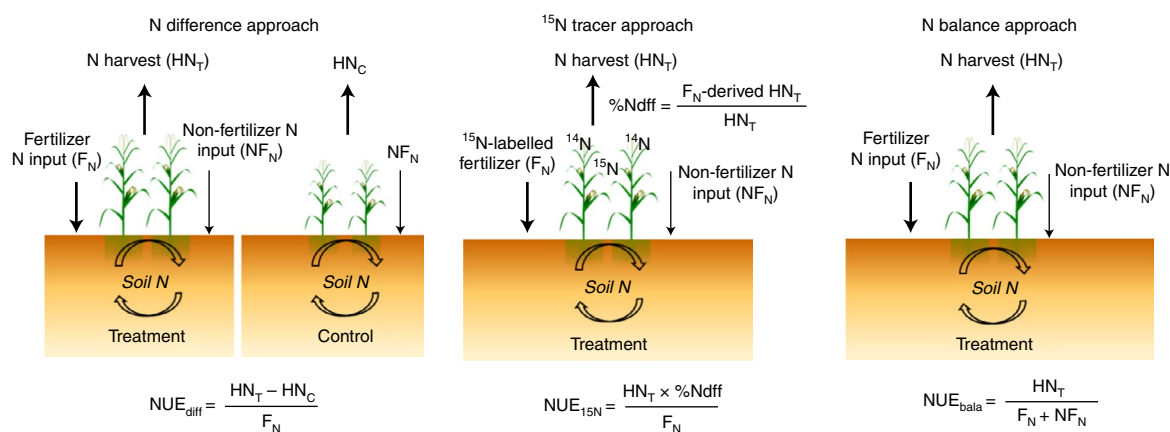


Fig. 1 | Three approaches for quantifying NUE in cropping systems. The figure shows, from left to right, the nitrogen difference approach, the ^{15}N tracer approach and the nitrogen balance approach. F_N , fertilizer nitrogen inputs; NF_N , non-fertilizer nitrogen inputs (including nitrogen deposition, asymbiotic nitrogen fixation and so on); HN_C , harvested N in the control plots (without nitrogen fertilization); HN_T , harvested N in the treatment plots (with nitrogen fertilization); $\%Ndff$, the fraction of harvested nitrogen derived from in-season-applied nitrogen fertilizer. The clipart of the maize plant in the figure was downloaded from <http://clipartmag.com/plant-clipart>.

Table 1 | Comparison framework for NUE quantification approaches

Approaches	N difference approach (NUE_{diff})	^{15}N tracer approach ($NUE_{^{15}N}$)	N balance approach (NUE_{bala})
Definition	Harvested N in fertilized plots minus the harvested N in non-fertilized control plots, then divided by N fertilizer inputs	Applies fertilizer with ^{15}N tracer and tracks the proportion of ^{15}N harvested in the crop product	Harvested N divided by all N inputs
Formula ^a	$= (HN_T - HN_C) / F_N$	$= (HN_T \times \%Ndff) / F_N$	$= HN_T / (F_N + NF_N)$
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 loss
Soil legacy effect	Largely excluded for short-term experiments	Not considered for single-season experiments	Partly or all included based on soil N status ^b
Requirement for soil N status	No requirement	No requirement	Change in soil N stock is low or negligible compared with total N input and total N output (quasi-steady-state)
Application on spatial scales	Plot, field	Confined microplot, plot, field	Field, watershed, region, nation or world
Application on temporal scales	Single to multiple growing seasons	Often conducted for a single growing season	From a single growing season to multiple decades
Data source	Mostly field trials	Mostly field trials	Mostly statistical data or survey data
Appropriate use	Characterize the immediate response of the crop to N fertilization under different measures or practices	Partition various fates of fertilizer N at relatively small space-time scales	Evaluate the resource and environmental performances of N input in cropland
Mean values in China	0.30 ($n=151$) ⁷ ; 0.27 ($n=667$) ⁸ ; 0.35 ($n=461$) ⁹	0.37 ($n=92$) ¹⁰ ; 0.36 ($n=216$) (a synthesis of published values, Supplementary Table 2)	0.68 ^{c,11}
Mean values on a global scale	0.48 ^{c,19} ; 0.47 ($n=748$) ⁶ ; 0.48 ($n=452$) ²⁰	0.44 ($n=804$) ⁶ ; 0.42 ($n=622$) ²⁰ ; 0.42 ($n=88$) ¹⁴	0.62 ^{c,1}

Definition, calculation, experimental settings and mean NUE values in cereal cropping systems (mainly wheat, rice and maize) are shown for three approaches: NUE_{diff} , $NUE_{^{15}N}$ and NUE_{bala} . ^aSee the legend of Fig. 1 for definitions of abbreviations. ^bOnly when the soil nitrogen status is in a steady state can the soil legacy effect of nitrogen input in the current season (to subsequent seasons) be offset by the soil legacy effect of nitrogen input in the previous seasons (to the current season). ^cFor three papers which calculated NUE values with grain nitrogen uptake, we estimate the NUE for aboveground nitrogen (grain + aboveground straw) as 1.45 times the NUE for grain nitrogen according to their empirical ratio.

efficiencies for F_N and NF_N are different, this difference may not fully account for the differences in the NUE values between approaches (Extended Data Fig. 2).

The major driver for the remaining differences between NUE_{bala} and the other two approaches is the legacy effect of nitrogen fertilization during previous seasons. Fertilizer nitrogen inputs not only supply plant nitrogen needs for the season of application but

also replenish soil nitrogen and support the maintenance of the long-term nitrogen supply in the soil¹⁰. With the exception of newly formed croplands, most farms have a history of fertilizer or manure use. This commonplace legacy or replenishment effect of fertilizer application indicates that a long-term view of NUE assessment is necessary (Fig. 2b,c). However, often due to logistical constraints, experiments for determining NUE are usually conducted for one

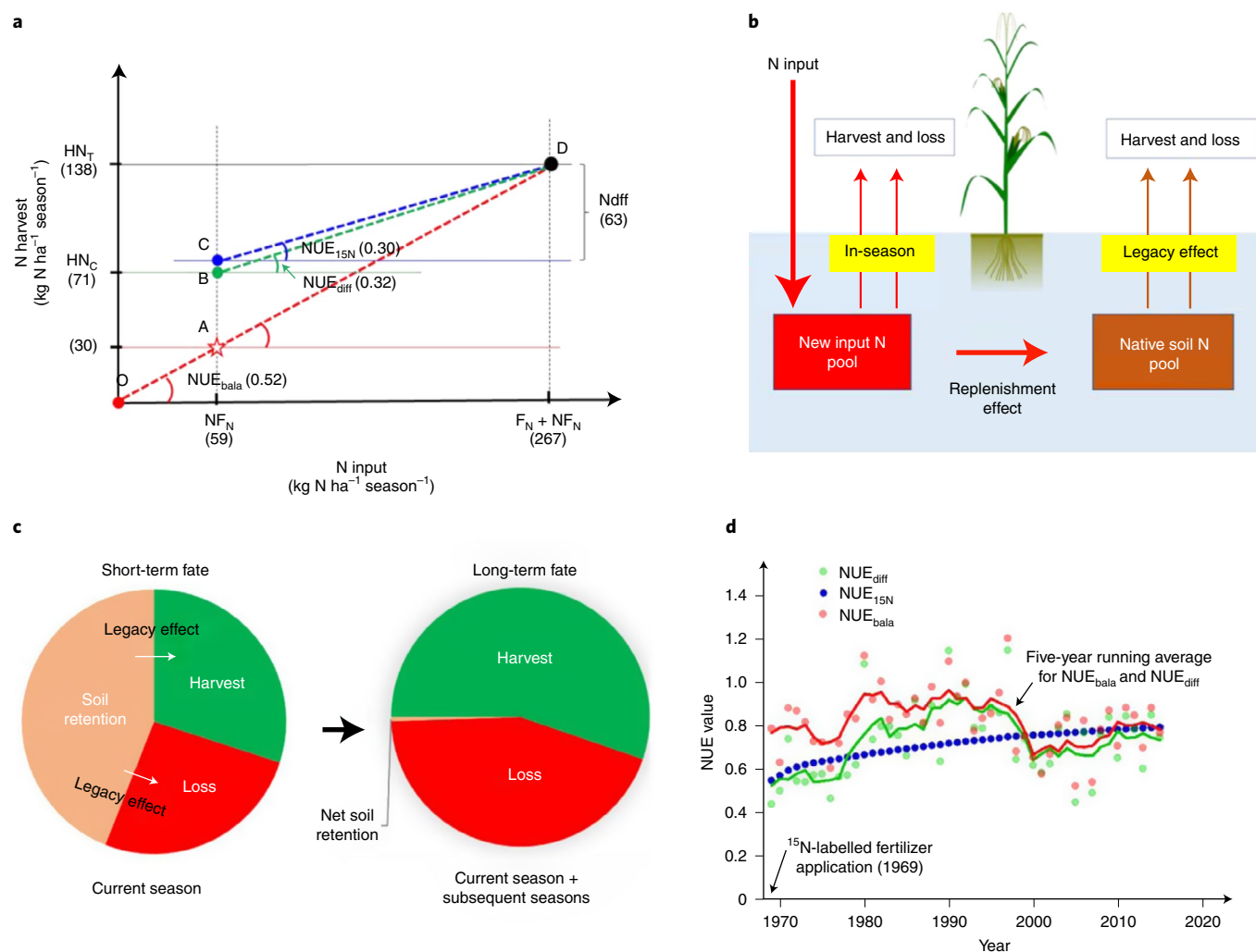


Fig. 2 | Major NUE quantification approaches and the influence of soil legacy effect. **a**, The definition of NUE_{diff} , $\text{NUE}_{15\text{N}}$ and NUE_{bala} under the same observation framework. See Fig. 1 caption for definitions of abbreviations. NUE_{diff} , $\text{NUE}_{15\text{N}}$ and NUE_{bala} correspond to the slopes of lines BD, CD and OD, respectively. Numbers in parentheses are from an example developed for the Chinese cereal cropping system (including wheat, rice and maize). Points B, C and D are determined by observations, whereas point A is determined as the cross-point of lines OD and BC. **b**, Schematic representation of the legacy effect in the cropping systems and its influence on NUE quantification. NUE_{diff} and $\text{NUE}_{15\text{N}}$ measure the ‘harvest’ nitrogen directly from the nitrogen input during the same season (red on the left), whereas the NUE_{bala} approach measures both ‘harvest’ nitrogen directly from the nitrogen input during the same season (red on the left) and ‘harvest’ nitrogen from soil turnover (brown on the right). The clipart of the maize plant in the figure was downloaded from <http://clipartmag.com/plant-clipart>. **c**, The change in fertilizer-nitrogen fate in the cropping systems over time, based on in situ ^{15}N tracer trials. This panel demonstrates that the nitrogen input retained in soil during the current season will probably be taken up as harvested crop product or be lost to the environment in the subsequent seasons. The size of each arrow and pie slice in **b** and **c** do not represent exact quantities (they are simple qualitative illustrations of possible contributions and shares of fertilizer nitrogen input and can be adapted to actual observation values for a given site or production system). **d**, An example of potential changes in NUE_{diff} , $\text{NUE}_{15\text{N}}$ and NUE_{bala} with long-term observations.

to several growing seasons with different considerations of legacy effects, leading to divergence in the results. With single-season observations, the NUE_{diff} and $\text{NUE}_{15\text{N}}$ approaches reflect the fertilizer recovery efficiency 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 a quasi-steady-state of soil nitrogen stocks, and does not exclude the long-term legacy effects of nitrogen inputs but may over- or underestimate the actual NUE if notable mining or accumulation of soil nitrogen occurs during the observation period (Table 1). Therefore, under the assumption of negligible NF_N or similar efficiency of F_N and NF_N , the difference between NUE_{bala} and single-season NUE_{diff} or $\text{NUE}_{15\text{N}}$ (for example, the difference between 0.52 and ~0.30–0.32 in the Chinese cereal cropping system example shown in Fig. 2a) can be used to estimate

the size of the legacy effect of applying nitrogen fertilizer. Soil type and local agronomic practices may influence the size of the legacy effect. Generally, soil with high nitrogen buffering capacity (for example, high turnover rate of soil organic nitrogen) or with low fertilizer nitrogen input tends to enlarge the difference between NUE_{bala} and the other two approaches (Supplementary Discussion 1).

Differences also exist between NUE_{diff} and $\text{NUE}_{15\text{N}}$ assessments but these are generally small in most studies (for example, <0.1 in Table 1). Soil scientists and agronomists have devoted extensive efforts to examining the potential causes of these differences^{4–6}, such as the change of native soil nitrogen supply caused by nitrogen fertilization through biological or non-biological processes. In addition, the ‘diminishing return’ of yield response to nitrogen input may also contribute to the differences (Supplementary Discussion 2).

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 probably decrease as soil nitrogen stock is continuously depleted without replenishment from additional nitrogen inputs¹² (Extended Data Fig. 3), while the cumulative %Ndff will probably increase as more ^{15}N will be recovered due to the pulse addition of ^{15}N tracer (that is, points B and C will probably move towards point A in Fig. 2a). Consequently, the observed NUE_diff and the cumulative $\text{NUE}_{15\text{N}}$ will probably increase as observation is conducted for a longer period (Fig. 2d). Moreover, the moving averages of the NUE_bala over several years under consistent management practices tend to be stable, despite the fluctuation caused by year-to-year yield variation, because the average annual soil nitrogen stock change tends to be negligible compared with the annual nitrogen fertilizer inputs over a long period¹³. Consequently, the assessments from the $\text{NUE}_{15\text{N}}$ and NUE_diff approaches tend to converge with that from the NUE_bala approach for long-term observations (Fig. 2d).

Choosing appropriate approaches

Overall, the three principal approaches to NUE quantification can produce divergent results even for the same plot or production system. While divergent results may generate insights in cropland soil and plant nitrogen dynamics, they also indicate that the comparison of NUE across plots or production systems should be based on a carefully chosen and consistently implemented NUE quantification approach to avoid inherent biases introduced by different approaches.

Fortunately, an appropriate approach can be chosen by identifying the goal of the assessment and comparison, as well as the associated logistical requirements, including cost (Table 1). For example, NUE_diff is a straightforward and cost-effective approach to assess the short-term response of harvested nitrogen to nitrogen fertilization under different environments or management conditions, but it is often difficult to perform in an actual farming operation because it is hard to convince farmers to devote a portion of their land to produce low yields due to lack of nitrogen fertilization. $\text{NUE}_{15\text{N}}$ is most accurate in tracing the transformation, absorption, transfer and transport of nitrogen 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 offers great advantages in evaluating the resource and environmental performances of nitrogen inputs in crop production, especially when the average change in soil nitrogen stock is small or even negligible compared with the annual nitrogen inputs during the observation period. First, NUE_bala is defined based on an assumption that soil nitrogen stocks are at a quasi-steady-state, which could be achieved in most cultivated croplands within a time frame shorter than the other two approaches (Fig. 2d). Therefore, ‘ $1 - \text{NUE}_\text{bala}$ ’ estimates the total nitrogen potentially lost to the environment as the fraction of nitrogen inputs and consequently has been considered as a ‘risk measure’ for nitrogen use¹. Second, NUE_bala is based on data more readily available from farm to national scales³. For example, grain yield and nitrogen fertilizer rates are typical values used in farmers’ book-keeping, and they are commonly collected in national or regional surveys or statistics.

It should be noted that, irrespective of which approach is used, short-term observations are limited in reflecting the long-term effect of changing management practices¹⁴. First, crop yield and nitrogen uptake vary from year to year due to changing weather conditions and consequently affect the NUE assessment. Second, the actual impact of the new management practices on yield and NUE may be buffered by a soil legacy effect. For example, some agronomic measures (for example, optimum fertilization,

plastic mulching, biochar application) combined with fertilizer rate reduction (for example, 30–60%) are frequently reported as being effective for improving NUE_diff or $\text{NUE}_{15\text{N}}$ while maintaining crop yields in China^{15,16}. 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 nitrogen supply capacity, as well as yield and NUE, in the long term. Consequently, to assess the impacts of different management practices on NUE, it is important to implement long-term trials when possible, and consider the influence of soil legacy effect when interpreting short-term observations.

Methods

To show the difference and connection among the three principal NUE quantification approaches, we constructed two examples based on values from the existing literature. One example is a Chinese cereal cropping system parameterized according to the proposed conceptual framework with values synthesized from published field observations and farm surveys. The other example is developed based on long-term observations to demonstrate the potential long-term dynamics of the three NUEs.

NUE_diff and $\text{NUE}_{15\text{N}}$ have been mostly applied to evaluate or trace the use of synthetic fertilizer, and most studies used in developing these examples report aboveground biomass nitrogen as the harvested nitrogen. As a result, we consider F_N as synthetic nitrogen fertilizer and include all aboveground biomass nitrogen as harvested nitrogen in both examples to enable a comparison across approaches with consistently defined terms. The definition for F_N could be adapted to assess the efficiency of organic fertilizer, and the definition of harvested nitrogen could be adjusted based on additional information about straw removal and utilization, as long as these terms are defined consistently across three approaches to enable a fair comparison. However, these tests are beyond the scope of this study.

Chinese cereal cropping system. Based on a review of published field observations and farm surveys for cereal cropping systems in China, the synthetic fertilizer input (F_N), non-synthetic input (NF_N) and harvested N (HN_T) are found to have average values of 208, 59 and $138 \text{ kg N ha}^{-1} \text{ season}^{-1}$, respectively (Fig. 2a; data sources are summarized in Supplementary Table 4). HN_C is calculated as the product of HN_T and the ratio of HN_C to HN_T (that is, $138 \times 51.4\% = 71 \text{ kg N ha}^{-1} \text{ season}^{-1}$). The ratio of HN_C to HN_T is estimated based on observed yield response and nitrogen-concentration response to fertilizer nitrogen input for Chinese cereal cropping systems (Supplementary Fig. 1, Supplementary Table 5). The harvest nitrogen derived from the fertilizer applied during the same season (Ndff) was estimated as the product of HN_T and %Ndff (that is, $138 \times 46\% = 63 \text{ kg N ha}^{-1} \text{ season}^{-1}$). To estimate %Ndff, we synthesized observations from ^{15}N tracer studies for Chinese cereal cropping systems (Supplementary Table 2) and identified the statistical relationship between %Ndff and $\text{HN}_\text{T}/F_\text{N}$ (Supplementary Fig. 2). Based on this relationship, %Ndff is predicted to be 46% when F_N and HN_T are 208 and $138 \text{ kg N ha}^{-1} \text{ season}^{-1}$. The soil nitrogen stock for the Chinese cereal cropping system could be considered at a quasi-steady-state based on national soil censuses between 1980 and 2008¹³.

Long-term dynamics of NUEs. To simulate long-term changes in NUE_diff , $\text{NUE}_{15\text{N}}$ and NUE_bala , we used data on nitrogen fertilizer inputs and nitrogen harvests from the Rothamsted Broadbalk Wheat Experiment from 1969 (<http://www.era.rothamsted.ac.uk/>). The harvested nitrogen values in treatments receiving normal rates of phosphorus, potassium and magnesium fertilizer but receiving 0 and 144 kg ha^{-1} nitrogen fertilizer were selected as HN_C and HN_T in this simulation. To calculate NUE_bala , the non-fertilizer nitrogen input was estimated as the sum of the annual wet deposition record¹⁷ and a uniform $15 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ symbiotic nitrogen fixation.

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 plausible $\text{NUE}_{15\text{N}}$ observation record using the following assumptions: (1) ^{15}N labelled fertilizer was applied in 1969 at the rate of 144 kg N ha^{-1} , and the same rate of non-labelled fertilizer was applied in the subsequent seasons; (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 France¹⁸ (Supplementary Fig. 3). The original data used to construct Fig. 2d can be found in Supplementary Table 6.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

This work used data collected from a variety of publicly available sources. See the references in the main text and Supplementary Information for data specification.

Code availability

The code used for this analysis is available from the corresponding author on request.

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Author contributions

Z.Q., X.Z. and Y.F. designed the study. Z.Q. and X.Z. collected data and conducted calculations. Z.Q., X.Z. and Y.F. led the analysis. All authors contributed to writing and revisions.

Competing interests

The authors declare no competing interests.

Additional information

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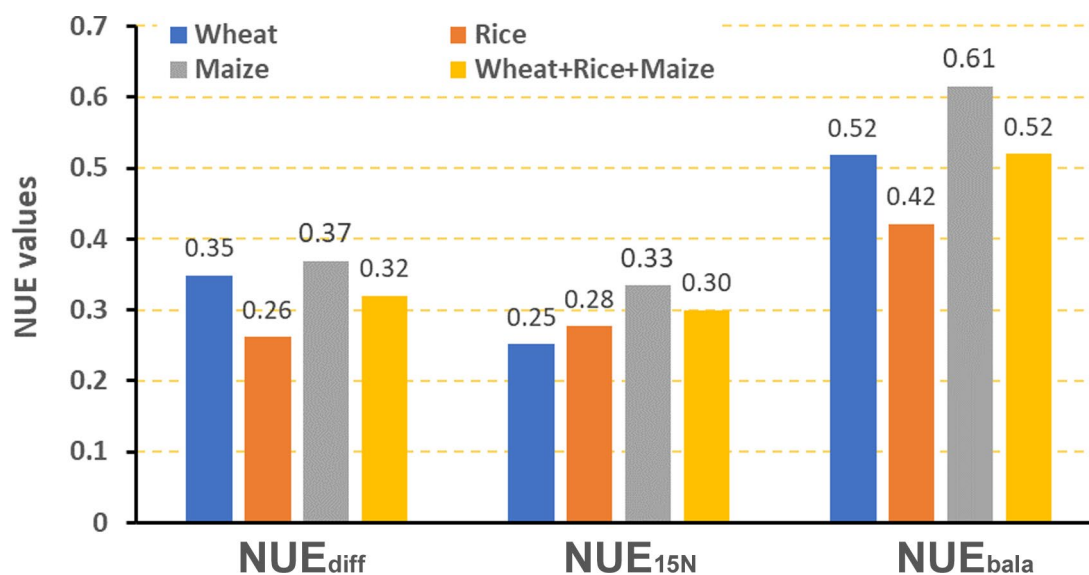
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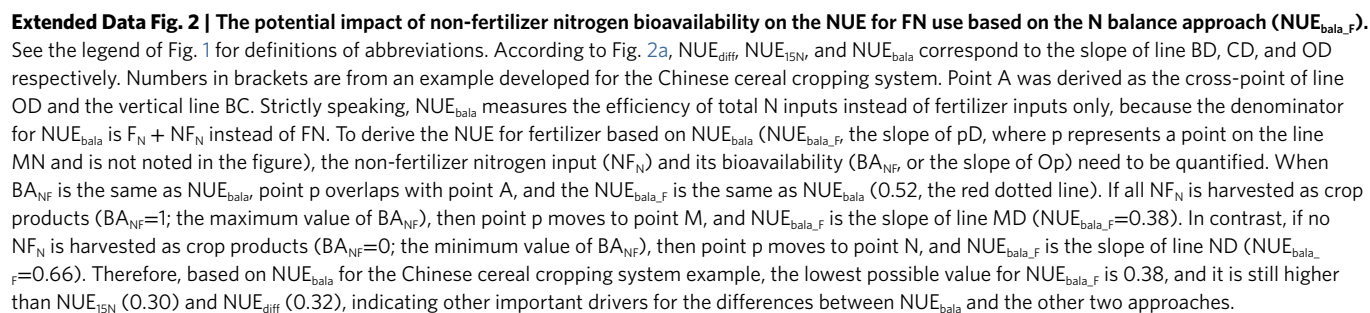
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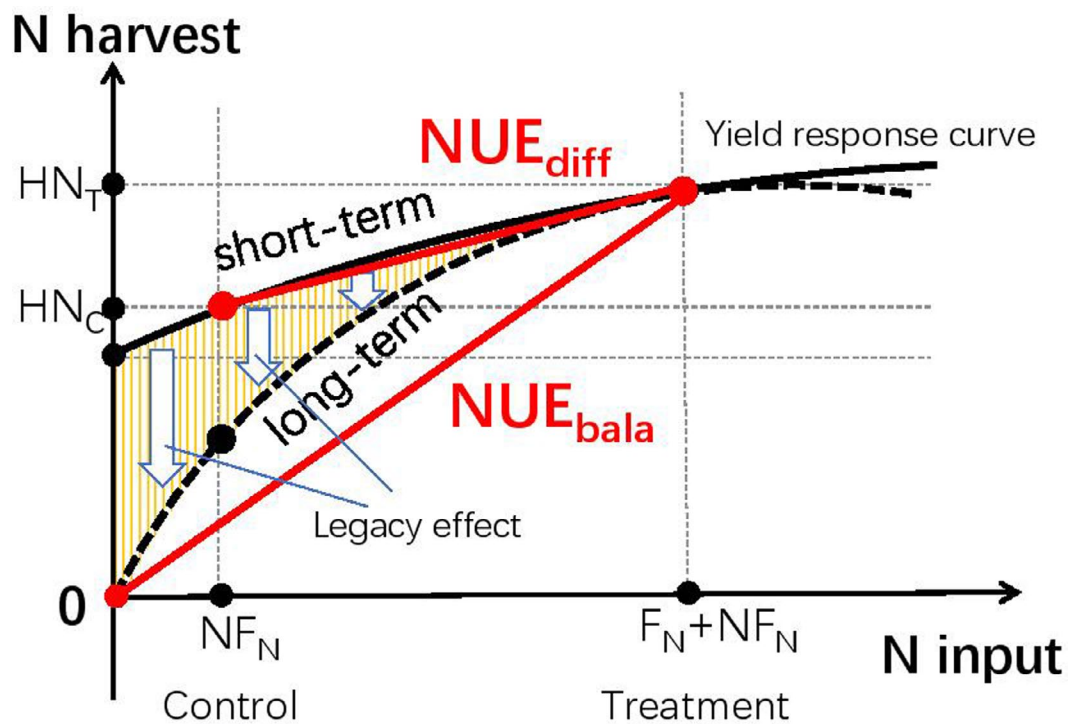
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Extended Data Fig. 1 | The average NUE values estimated by NUE_{diff} , NUE_{15N} and NUE_{bala} approaches in the Chinese wheat, rice, and maize cropping system. Equations in Table 1 ($NUE_{diff} = (HN_T - HN_C) / F_N$; $NUE_{15N} = (HN_T \times \%Ndff) / F_N$; $NUE_{bala} = HN_T / (F_N + NF_N)$) were used to estimate the average NUE_{diff} , NUE_{15N} and NUE_{bala} for the three major cereal crops within China's cereal cropping system. Data sources: the average $\%Ndff$ was from Supplementary Table 2; HN_C was calculated as the product of HN_T and the ratio of HN_C to HN_T which was estimated based on the observed yield response to fertilizer nitrogen input in Supplementary Fig. 4 and the observed nitrogen concentration response to fertilizer nitrogen input in Supplementary Table 5; the average HN_T and F_N were from Supplementary Table 3; the average NF_N was from Supplementary Table 4 (asymbiotic N fixations were estimated as 30 kg N ha⁻¹ for rice, and 10 kg N ha⁻¹ for wheat or maize). See Fig. 1 caption for definitions of abbreviations.





Extended Data Fig. 3 | The yield response curves from short-term and long-term observations, and the relationship between observed NUE_{diff} and NUE_{bala} . A typical yield response curve based on field trials shows a “diminishing return” to N inputs. For experimental sites that have been under fertilizer N treatment over a period of time, the yield observed at the control plot tends to decrease over time (the red point on the vertical dashed line of NF_N moves downward), mainly due to the gradually reducing legacy effect of N input before the setting of the control plot. See the legend of Fig. 1 for definitions of abbreviations. The slopes of red lines are NUE_{diff} and NUE_{bala} .

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- ☒ ☐ For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- ☒ ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- ☒ ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- ☒ ☐ Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection No software was used to collect or download the data. All data in our manuscript were from literature, which were described clearly in the Method section.

Data analysis All data analysis was performed in Excel 2010 (Microsoft). Figures were made by PowerPoint 2010 (Microsoft) and Sigmaplot 14.0 (Systat).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All data in our manuscript (figure 2a and 2d) were from the literature, which were described clearly in the Method section and Supplementary Information section.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study is about concept and question of nitrogen use efficiency (NUE). We proposed a conceptual framework, with supporting case studies, to identify the differences and connections among three commonly used approaches for defining and quantifying NUE.
Research sample	1) NUE calculations for the Chinese cereal cropping system: data from several published papers. 2) Simulating NUEdiff, NUE15N, and NUEbala changes in long-term experiments: The data sources were from the Rothamsted Broadbalk Wheat Experiment (www.era.rothamsted.ac.uk/). The proportions of 15N harvested (%Ndff) in the first season and in subsequent seasons were from 28-year-long 15N tracer experiment (Selbio et al., 2013).
Sampling strategy	No sample was sampled in this study.
Data collection	All data in our manuscript (figure 2a and 2d) were from the literature (publicly available, existing datasets), which were described clearly in the Method section.
Timing and spatial scale	1) NUE calculations for the Chinese cereal cropping system: data are averages at national scale during 2005-2014. 2) Simulating NUEdiff, NUE15N, and NUEbala changes in long-term experiments: data are from a long-term experiment during 1969-2015.
Data exclusions	No data was excluded.
Reproducibility	Not applicable.
Randomization	Randomization is not relevant to this study, as no treatment is applied.
Blinding	Blinding is not relevant to this study, as no treatment is applied. We constructed an example based on the synthesis of values from the literature (mainly obtained by national on-farm surveys and field trials).
Did the study involve field work?	☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging