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Critical assessment of nitrogen use efficiency indicators: Bridging new and old paradigms to improve sustainable nitrogen management

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ABSTRACT

Environmental indicators for nitrogen (N) use efficiency (NUE) based only on N inputs and N removal are becoming widely used in science, policy, and commercial supply chains to track the sustainability of food production. However, these indicators do not reflect the contribution of inherent soil productivity, which can supply half of crop demand and is therefore a core principle in determining how much fertilizer is needed and the corresponding risk of N losses. Using a global dataset of optimal N rates for crop production, we evaluated the performance of conventional (N recovery efficiency) and simplified NUE indicators to understand their relationship and respective limitations, helping inform policy efforts for simultaneously meeting food production and sustainability goals. A key finding is that conventional agronomic approaches designed to optimize crop productivity and profit related to N fertilizer inputs have tradeoffs for environmental performance, with only 35 and 31 % of observations (n=448) falling within sustainable ranges for NUE. Meanwhile, simplified NUE indicators such as N balance or the ratio of N outputs to inputs were unable to detect sites with inherently low N recovery efficiency and high risk of N losses, highlighting a weakness of neglecting soil N supply in their calculations. Together these results suggest the need for a combined approach that merges insights from locally available agronomic data on N recovery efficiency with global environmental thresholds for NUE. Using our findings as a case study, we propose new steps forward for evaluating NUE in different cropping systems and regions to enhance food security while mitigating N pollution.

1. Introduction

Nitrogen (N) fertilizer use is essential to support global crop production and ensure food security (Bonilla-Cedrez et al., 2021; Cassman et al., 2002; Ladha et al., 2020). However, agricultural N losses are a large contributor to environmental N pollution through gaseous emissions and nitrate leaching leading to ecosystem degradation and climate change (Clark et al., 2020; Halpern et al., 2022; Houlton et al., 2019). Tracking the efficiency of N fertilizer use and related N losses has become a priority for the scientific community and will be a major challenge for decades to come (Clark et al., 2020; Sutton et al., 2021). In general terms, N use efficiency (NUE) is the ratio between an output (crop yield or N removal) and an input (N supply, derived from inorganic or organic N sources) (Congreves et al., 2021; Dobermann, 2007). Yet, because this term has multiple components that can be quantified and expressed in different ways, reporting and interpretation of NUE metrics is inherently complex (Ladha et al., 2005), with different approaches leading to different conclusions (Ladha et al., 2020). Currently, there is a widespread shift in science and policy towards the use of simplified NUE indicators for estimating environmental risk that can be implemented with minimal data inputs (Quan et al., 2021; Tingyu et al., 2020). However, the consequences of this change compared to historical methods for evaluating NUE in agricultural field experiments remain unexplored. To guide future policy on appropriate indicators for simultaneously meeting food production and sustainability targets (Cassman and Grassini, 2020; Kanter et al., 2020), there is a critical need

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to investigate relationships among new and old frameworks to understand how their outcomes differ and identify opportunities for improvement.

Nitrogen use efficiency indicators most commonly used by the agricultural community are based on crop response to applied fertilizer and therefore account for inherent soil productivity (i.e., comparing yields in fertilized and unfertilized plots; Ladha et al., 2020). However, this comparison requires additional effort and cost which prevents rapid NUE assessments at scale. To overcome this challenge, less sophisticated indicators based only on N inputs and crop N removal are becoming widely used in research (Eagle et al., 2020), policy (Dalgaard et al., 2014), and commercial sectors (McLellan et al., 2018). One such indicator is the simplified N balance (N_b) which is calculated as N inputs (e.g., fertilizer N) minus N outputs (e.g., grain removal) (McLellan et al., 2018; Quan et al., 2021). A second indicator utilizes the same N_b components, but is expressed as the ratio of N outputs to N inputs (NUE_b), as advocated by the EU N Expert Panel (EU Nitrogen Expert Panel, 2015; Table 1; Fig. 1B). Studies are increasingly implementing these indicators at field, farm, and regional scales as a proxy for the proportion of available N inputs utilized by the cropping system and, consequently, the risk for environmental N losses (Quemada et al., 2020; Silva-Campa et al., 2010; Tamagno et al., 2022; Tenorio et al., 2020). While beneficial for tracking the sustainability of agricultural production with minimal information required, these two metrics primarily serve as retrospective indicators of N loss that can only be calculated after the growing season (Quan et al., 2021). A critical examination of N_b and NUE_b compared to traditional methods for evaluating NUE in the agronomic discipline is lacking, which is an important step to identify overlooked aspects or potential limitations.

1.1. Nitrogen frameworks

The conceptual framework of NUE_b proposed by the EU Nitrogen Expert Panel (2015) can be graphically presented using a two-dimensional input-output diagram (Fig. 1B). The environmental performance of a system is based on N inputs versus outputs, where the envelope functions delineate safe boundaries of NUE_b to indicate risks of soil mining or inefficient N use. These limits can be combined with a desired minimum N output or yield level in harvested grain and maximum level of N_b as an indicator for potential N losses to the environment. Together these target values identify a 'safe operation area' which considers minimum productivity levels, potential N losses, and soil mining risks. Even though target values may vary depending on production system characteristics and environmental conditions, this graphical representation provides a diagnostic framework to identify environmental risks and production inefficiencies (Ladha et al., 2020; Quemada et al., 2020). It should be noted that N input and output data is obtained at the field-level, while efforts for tracking sustainability and reporting outcomes are currently happening at much larger (regional or national) scales.

On the other hand, in the agronomic and soil science communities there is a long and rich history of applied field research for improving N management and NUE, with many indicators available (Congreves et al., 2021; Fageria and Baligar, 2005; Huggins and Pan, 1993; Ladha et al., 2005; Moll et al., 1982). In contrast to NUE_b and N_b, a core principle is accounting for soil indigenous N supply in a given growing season to define NUE, which serves to minimize the need for external N inputs for meeting crop N demand. Field trials are used to quantify crop response to applied N fertilizer based on i) unfertilized crop N uptake which indicates inherent soil productivity (i.e., soil N supply) and ii) maximum yield representing the point at which yield no longer increases with higher N rates (agronomic optimum N rate; AONR). This experimental approach provides information to calculate different NUE metrics that focus on fertilizer, plant, or soil N use (see Ladha et al., 2005 or Dobermann et al., 2007 for a thorough review).

The magnitude of crop N removal (i.e., difference between fertilized

Table 1
Frameworks and definition of NUE metrics utilized in this study.

Nitrogen framework	Indicator	Definition
Conventional agronomic approach	**Agronomic optimum N fertilizer rate (AONR):**	Fertilizer N rate at which crop yield is maximized (i.e., agronomic optimum yield; AOY). Beyond this rate, crop yield response is negligible or lower than AOY (red point in Fig. 1A).
	Economic optimum N fertilizer rate (EONR):	Fertilizer N rate at which expected profits are maximized. The EONR is the N rate where the slope of the yield-to-N rate equals the fertilizer:grain price ratio (green point in Fig. 1A).
	NUE terms for calculating indicator	Most common terms utilized would be outputs (e.g., grain yield, grain N removal, plant N uptake) as numerator and inputs (e.g., N from soil, fertilizer, or both) as denominator. The most common and widely used metrics are agronomic efficiency (AE_N; ratio between yield and N supply), the recovery efficiency (RE_N; ratio between plant N uptake to N supply) and the physiological efficiency (PE_N; ratio of yield to plant N uptake). All yield or plant N uptake refers to yield of fertilized plot compared to unfertilized control.
EU N Expert Panel - Nitrogen use efficiency indicator framework	**N input**	Fertilizer N plus other N inputs in the system, when available. Including atmospheric deposition, biological N_2 fixation, crop residues, manure N or other organic inputs, soil N mineralization. This information is not always available. In this study, only N from fertilizer is considered for the N inputs.
	N output	The N output in harvested products (i.e., grain N removal).
	NUE_b	Calculated as N output / N input. For this study, the desired NUE_b range was between 0.50 and 0.90 to avoid N pollution or soil mining issues. Optimum thresholds can vary depending on the variables of the system (crop rotation/type, management, soil fertility, etc.)
	N balance (N_b)	Difference between N input and N output. Also called N surplus or partial N balance. A maximum N_b of 67 kg N ha^{-1} is depicted (solid line; Fig. 1B) after which the risks for N losses are higher. The optimum range adopted in this study is between 22 and 67 kg N ha^{-1}.
	Minimum desired N output	The minimum harvested N output. Represents a desired crop productivity target for the system. The value used in this study is 67 kg N ha^{-1}.

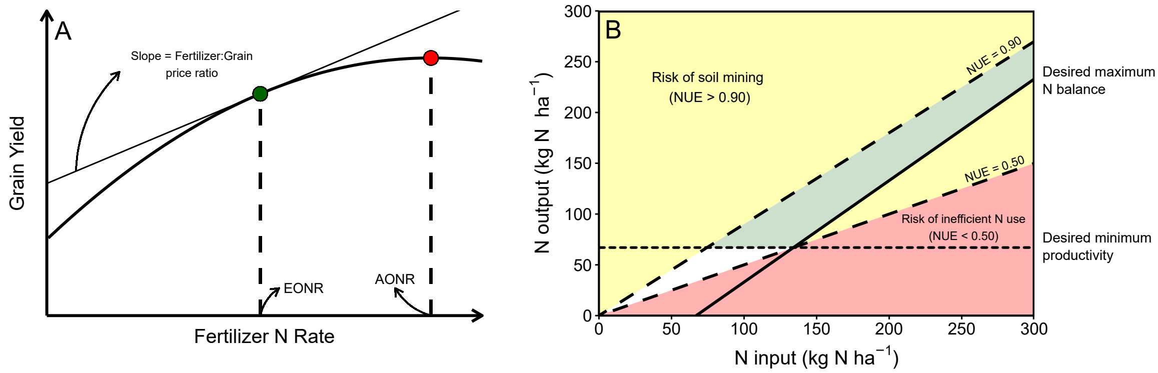

Fig. 1. **:** Graphical representation of (A) the historical NUE paradigm based on optimizing economic and agronomic fertilizer N rates (EONR and AONR, respectively) by accounting for both soil N supply and relative crop N demand, and (B) the more recently developed conceptual framework of NUE_b and N_b indicators focused on environmental performance to avoid inefficient N use or soil mining, as proposed by the EU Nitrogen Expert Panel (2015). The green area in B represents the safe operation area enclosed by minimum N productivity of 67 kg N ha^{-1} (horizontal dashed line), desired NUE_b ranges between 0.50 and 0.90 (dashed lines) and the maximum N_b of 67 kg N ha^{-1} (solid line).

plot and non-fertilized control) divided by a given N rate is commonly known as recovery efficiency of N (RE_N; Ladha et al., 2005), indicating the relative amount of fertilizer absorbed by the crop. Thus, higher RE_N values will typically correspond to lower soil N supply, indicating substantial yield gains per unit N fertilizer addition (Dobermann, 2007; Xu et al., 2014). Likewise, some sites with high soil N supply relative to crop demand show little response to applied N fertilizer (Ahrens et al., 2010; Chuan et al., 2013b; Johnson, 1991), indicating other components of the cropping system are likely yield-limiting (e.g., water availability, pests or disease, or soil compaction, among others). While N fertilizer addition can generate higher revenue through increased crop yield, fertilizer costs are also important to consider. Profits are maximized by targeting the economic optimum N rate (EONR; Fig. 1A) which provides the greatest returns per unit of N addition (Pannell, 2017; Sawyer et al., 2006). Generally, EONR produces slightly lower yields than AONR but this is offset by the reduction in N fertilizer inputs and associated costs, which also delivers environmental benefits (Zhao et al., 2017).

Decades of research and innovation have produced a variety of tools to identify EONR (Morris et al., 2018), helping farmers optimize N management during the growing season based on an understanding of both anticipated crop N demand and soil N supply under different environmental conditions. However, given the rapidly growing emphasis on N_b and NUE_b as performance metrics for sustainable food systems, further analysis is required to understand discrepancies and potential weaknesses of these different approaches. These two frameworks (Fig. 1) have different motivations (environmental vs. agronomic), methods of calculation, and underlying assumptions about the contribution of soil indigenous N supply over space and time (Quan et al., 2021; van Grinsven et al., 2022). Despite these differences, we are not aware of studies critically examining the intersection of these two paradigms using quantitative analysis applied to a consistent dataset. Moreover, most research assessing N_b or NUE_b is focused on typical management practices to establish a baseline understanding of NUE across farms or regions (Quemada et al., 2020; Tenorio et al., 2020), with studies often concluding that tools should be implemented for improved N management (Cardenas et al., 2019; de Klein et al., 2017). With this in mind, there is a growing body of research suggesting that classical agronomic approaches to find optimal N rates are inefficient given the uncertainties associated with soil N mineralization and dynamic crop N demand during the season. Instead, researchers have developed N nutrition index (NNI) as an alternative method for more accurately estimating crop N status and the need for additional N inputs, accounting for the allometric relationship between N uptake and crop growth (Ciampitti and Lemaire, 2022; Lemaire and Ciampitti, 2020). This approach represents a change in paradigm in that it disregards soil N availability as the main external factor for determining fertilizer rates because crop N uptake is also coregulated by crop growth capacity (Briat et al., 2020; Lemaire et al., 2021).

The goal of this study was to compare agronomic (RE_N under optimized N management) and environmental frameworks (NUE_b and N_b) in terms of their performance, limitations, and implications for sustainability to inform policy discussions. To represent the historical paradigm of NUE based on crop response to applied N fertilizer, we used a global dataset of field trials to identify N rates that optimized yields (AONR) or profits (EONR). For each observation, RE_N, N_b, and NUE_b were calculated. The specific objectives were to i) determine how often safe boundaries for N_b and NUE_b are trespassed when N rates are optimized using recommended ranges as a case study, and ii) examine the role of soil N supply (unfertilized crop N removal) and crop N demand (crop N removal at AONR) as a controlling factor for decreasing the yield response to fertilizer, and consequently, RE_N. As results indicate that both frameworks have limitations, we also explore future steps for integrating and adapting agronomic and environmental frameworks into a joint approach for sustainable N management that can be tailored to specific cropping systems and regions.

2. Materials and methods

2.1. Data collection

The database was obtained from the International Plant Nutrient Institute (IPNI) and originated from a global literature search conducted in using Web of Science to retrieve peer-reviewed publications reporting crop response to commercial N fertilizer under field conditions between 1980 and 2017. Key words included “nitrogen”, “rate”, “economic”, “optimal”, “grain”, and “protein.” A second wider search was conducted for the following key words: “maize”, “wheat”, “canola”, “soil”, “nitrogen”, “yield”, “place”, “rate”, “tim*”, “response”, and “source”. The exact search terms are included in the Supplementary Information. Of the search results, 247 papers were deemed relevant according to details provided in the abstracts. Data were compiled from 101 studies that reported i) three or more fertilizer N rates (including an unfertilized control treatment), ii) crop yields, and iii) grain protein or N content or N concentration measurements. We excluded studies where temperature, radiation or atmospheric CO_2 were manipulated. The search was restricted to wheat, barley, maize, oats, rye, mustard, triticale, and canola. Data were transcribed from tables or extracted from figures using the Webplot Digitizer program (Ankit Rohatgi, 2022). In total, 448 yield response curves (Fig. S2) were compiled, making a total of 2237 observations. Studies were geographically distributed across different regions, however 41 % and 22 % of the observations were from the United States (US) and Canada, respectively (Fig. S1). It is likely that the geographical bias was due to the strict search criteria excluding studies not reporting N concentration or grain N uptake which are not commonly reported in many fertilizer response studies.

Crops were grouped according to their number of observations in maize, wheat, oilseeds (canola, yellow mustard) and 'other' comprising small grains crops (barley, triticale, rye, oats, sorghum). Grain yield was converted into dry mass using the reported grain moisture in each study. For each observation, grain N removal (kg N ha^{-1}) was calculated using the reported value or the grain yield multiplied by grain N concentration. In only 6 % of the observations, grain N concentration was estimated from protein concentration using a conversion factor of 6.25 for maize and 5.7 for all other crops.

2.2. Data analysis

Data was grouped by each unique curve, then crop yield and grain N response to N fertilizer were modeled by regression analyses using quadratic and quadratic-plateau equations. The best fit was determined by selecting the lowest root mean squared error (RMSE) between models. Once regression equations were individually selected according to best fit, the AONR was calculated as the N rate at which the predicted maximum grain yield (agronomic optimum yield; AOY) occurred. The highest N rate used in the trial was considered as AONR or EONR in cases where the estimation of optimums was higher than 10 % of the highest N fertilizer rate applied in the trial. A total of 448 response curves were included in the dataset comprising 300 quadratic and 148 quadratic-plateau models. The number of observations per curve ranged between four and eight. For each of these groups, the N removal at AONR was estimated using the predicted yield value at AONR and the relationship between grain N removal and N rate determined for each site-year.

The economic optimal yield (EOY) and EONR were calculated for each yield response curve by taking the first derivative of the equations and solving for a fertilizer to grain price ratio (Fig. 1A; Pannell, 2017). Historical fertilizer price ($ per kg N) for anhydrous ammonia and urea averaged 0.75 $ kg N^{-1} spanning a 15 year-period between 1999 and 2014 (NASS-USDA, 2022). Grain price was 0.138 $ kg^{-1} for the same period estimated from maize after showing a strong correlation ($R^2 >$ 0.75) with wheat, canola, and barley prices. Thus, the historical fertilizer to grain price ratio used here was 5.677. In this regard, recent studies have illustrated that relatively large changes in the N fertilizer: grain price ratio have relatively small impacts on EONR (Janovicek et al., 2021; Mandrini et al., 2022; van Grinsven et al., 2022)

2.3. N-related metrics and frameworks

In order to differentiate the influence of crop N demand and soil N supply on the overall yield response to N fertilizer in each site-year, we standardized this response using the N removed in the control treatment (N removal$_0$) as an estimate for soil N supply and the N removed at the AOY (N removal$_{AOY}$) as crop N demand. Thus, an estimate of the relative N supply-demand ratio (R_s) can be calculated as [1 - (N removal$_0$ / N removal$_{AOY}$)] (Fig. 2). Values close to 1 represent higher demand for N fertilizer (fertilizer-responsive sites) whereas values close to 0 are representative of flat response curves with less fertilizer demand (i.e., soil N supply met crop demand). It is important to note that in both cases, the absolute value of the unfertilized control can be lower or higher, meaning a flat response can occur at sites with relatively low or high unfertilized yields and vice versa. A similar metric has been proposed to measure the degree of synchrony between N supply and crop demand (Cassman et al., 2002). Likewise, the relative yield of an unfertilized control has been used as a proxy to quantify the influence of indigenous soil N supply to study nutrient use efficiency in wheat (Chuan et al., 2013b, 2013a), maize (Xu et al., 2014), or orchards (Li et al., 2019). To account for the effect of low and high soil N supply sites (high and low R_s, respectively), we grouped the observations into three

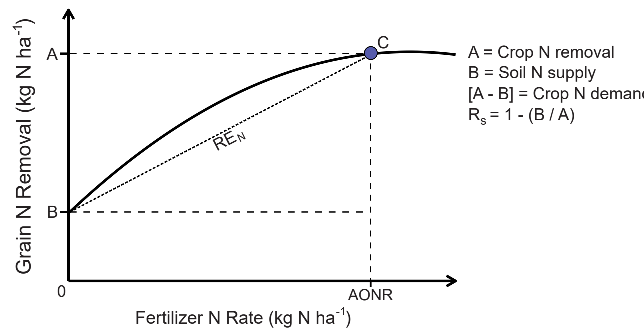

Fig. 2. : Theoretical response curve illustrating the relationship between grain N removal and fertilizer N rate in field trials, with terms used for calculating NUE represented by total crop N removal (A) at the AONR and the soil N supply (B). The slope between B and C represents the RE$_N$.

groups using the 25 and 75 % quantiles. A 'low' group for curves with R_s below 0.43, a 'medium' group comprising values between 0.43 and 0.66 and a 'high' group for R_s higher than 0.66. When R_s groups were plotted, regressions at the 50 % quantile were fit using the function '*rq*' from the '*quantreg*' R package (Koenker, 2017). All other linear regressions were conducted using R software (R Core Team, 2021).

The fraction of plant N in the calculation of RE$_N$ can be based on total plant N uptake or the grain N removal (Krupnik et al., 2004). Here, RE$_N$ was calculated for the agronomic and economic optimum N rates as the difference between grain N removal for the unfertilized control (*y*-intercept) and the AOY or EOY, divided by the corresponding AONR or EONR, respectively (Ladha et al., 2005). For each response curve, N_b (kg N ha^{-1}) was calculated as the difference between N inputs (AONR or EONR) and N outputs (grain N removal from the field at AOY or EOY). This metric is commonly referred to as N surplus or partial N balance by the EU Expert Panel Framework (EU Nitrogen Expert Panel, 2015). In this calculation, other N inputs (e.g., biological N_2 fixation from previous crops, net soil N mineralization, atmospheric deposition, etc.) or N outputs (e.g., straw removal) were not included due to data limitations for each site, consistent with previous studies that did not include net soil N mineralization or N_2 fixation (Mandrini et al., 2022; Silva et al., 2021; Tenorio et al., 2020). However, we explored the implications of this assumption by including all other potential sources of N inputs in the N input-output framework in a supplementary analysis. An estimate of non-fertilizer inputs was collectively added to optimum N rates to represent total N availability following van Grinsven et al. (2022), except with our approach grain N removal from the unfertilized plot was considered as a proxy for indigenous soil supply as it inherently includes all non-fertilizer inputs (biological N_2 fixation, soil N mineralization, atmospheric deposition).

Thresholds for N_b, NUE$_b$ and N inputs can differ across regions and farming systems depending on the acceptable level of environmental impacts (de Vries et al., 2021). In our study, we adopted a safety boundary between 22 and 67 kg N ha^{-1} for N_b, based on the framework proposed by the Environmental Defense Fund (EDF) to promote best N management practices and track environmental losses across the agri-food chain (EDF, 2020) and the NUE$_b$ target range of 0.50 and 0.90 from the EU N Expert Panel. The EDF program is currently active and its values are closely aligned with the maximum recommended by Quemada et al. (2020) of 68 kg N ha^{-1} for arable lands across European farming systems and with the safe planetary boundaries of 52 – 69 kg N ha^{-1} proposed by (Zhang et al., 2021). Moreover, studies exploring boundaries economically and environmentally sustainable at global or farm scale, have arrived to comparable thresholds (Bodirsky et al., 2014; de Vries et al., 2021; Steffen et al., 2015).

3. Results

3.1. Relationship among frameworks

There was wide variation in fertilizer N rates required to achieve AONR and EONR across studies (Fig. 3). Similarly, crop yields and grain N removal varied widely at a given level of N input. Based on these inputs and outputs, the majority of observations fell outside the safe zone delimited by 0.50 and 0.90 NUE_b, minimum and maximum N output, and N_b of 67 kg N ha^{-1}, respectively. The average NUE_b was 0.65 and 0.87 for agronomic and economics optimum N rates, respectively. From the total observations in the dataset (n=448), 35 % of the AONR (Fig. 3A) and 31 % of the EONR (Fig. 3B) fell inside the safety area. Average AONR and EONR were 147 kg N ha^{-1} (ranging 31–365 kg N ha^{-1}) and 122 kg N ha^{-1} (0–360 kg N ha^{-1}), respectively (Table S1). Lower EONR vs AONR, translated into slightly lower averages for grain N removal (85 vs 88 kg N ha^{-1}, economic vs agronomic, respectively) and lower N_b (36 vs 57 kg N ha^{-1}).

The proposed thresholds for N_b between 22 and 67 kg N ha^{-1} was largely surpassed by observations for optimized N rates in the dataset. Higher N_b was positively correlated with N inputs, for both AONR (Fig. S3A) and EONR (Fig. S3B; $p < 0.001$). However, for every kg N ha^{-1} increase in optimized N input, N_b was 5 % lower for EONR. At the AONR, N_b ranged between −61–291 kg N ha^{-1} and at the EONR it ranged between −68–291 kg N ha^{-1} (Table S1). Both approaches produced the majority of observations above and below the safety benchmarks of 22 and 67 kg N ha^{-1}, with 57 % and 63 % of observations outside this range for the agronomic and economic optimized N rates, respectively. A detailed summary of the calculated metrics is reported in the supplementary material Table S1 and Supplementary Data.

3.2. Influence of relative N supply-demand ratio

We used the relative N supply-demand ratio (R_s) to study the influence of soil N supply and crop demand on N-related metrics and the shape of crop responsiveness to N fertilizer. Higher R_s indicates a large response to applied N fertilizer while lower R_s indicates little response, often because factors other than N supply are limiting. Despite variability, AONR and EONR slightly increased when associated to R_s ($p<0.001$; Fig. 3A-B). However, EONR was more sensitive to changes in R_s with an increase of 15.1 kg N ha^{-1} for every 0.1 increase in relative yield compared to 8.5 kg N ha^{-1} for AONR. Likewise, higher R_s was positively associated with RE_N ($p<0.001$; Fig. 3C).

The strong influence of R_s on NUE_b and N_b was evident when comparing optimized N management under the EU N Expert Panel safety boundaries (Fig. 3). For AONR, 50 % quantile regression curves fit inside the NUE_b safe zone envelope function for all three R_s groups (Fig. 3A) without showing any clustering. Slopes were 0.64, 0.62, and 0.58 for the low, medium, and high group, respectively. However, for EONR (Fig. 3B) the group of low R_s (less responsive sites) were close to the boundaries of the NUE_b envelope ($NUE_b = 0.90$). The NUE slopes of the 50 % quantile regression were 0.88, 0.68, and 0.60 representing a percentage increase of 37, 9, and 3 % for the low, medium, and high, respectively in relation to AONR. The N_b showed a significant increase when regressed against R_s for both AONR and EONR (Fig. S5). In both cases negative N_b were associated with low R_s, however the slope for EONR was 85 % more sensitive than AONR to changes in R_s and both analyses portrayed a certain level of variability.

To assess the implication of our methodology which only considered N fertilizer rate as an input, we included a supplementary analysis to estimate non-fertilizer N inputs (represented by grain N removal from the unfertilized plots) in addition to the optimum N rate to determine the total inorganic and organic N inputs for each site-year (Fig. S4). As expected, the inclusion of non-fertilizer N sources in the calculation exacerbated the proportion of observations falling outside the safe zone (88 and 75 % for the agronomic and economic analysis, respectively), but in the direction of lower NUE_b values and thus, higher risk of N losses. For the AONR analysis, the low, medium and high group for R_s showed an average slope of 0.46, 0.49, and 0.50, respectively. Whereas the EONR observations showed higher average slopes of 0.57 for the low R_s group and 0.53 for the medium and high group.

3.3. Connecting the two paradigms

Comparing N_b and RE_N together (Fig. 5A) reflects the interaction between R_s groups and the effects of optimized N management (AONR and EONR). A large proportion of observations exceeding the low and high N_b benchmarks were associated with low RE_N values belonging to the low and medium R_s group. For AONR, 68 % of the observations (n=177) exceeding the N_b benchmarks had RE_N values of 40 % or less, with most of the observations (28 %) in the low R_s group (Fig. 5B). Similarly, for the same RE_N range, 58 % of the EONR observations (n= 166) were outside the N_b safety boundaries (Fig. 5C), of which 31 % belonged to the low R_s group.

Following the same approach for the NUE_b framework (Fig. 5D), observations outside the safe zone and below 40 % RE_N represented

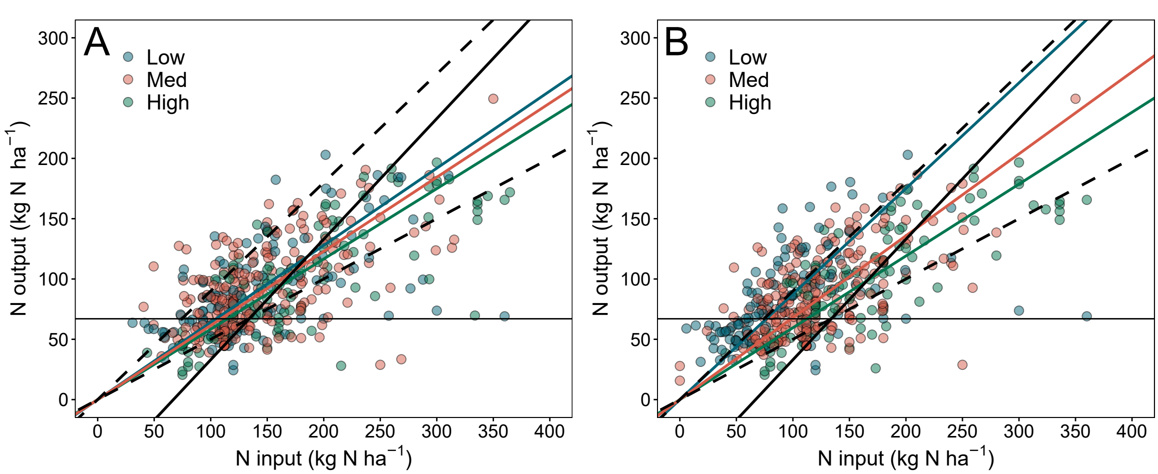

Fig. 3. : Relationship between N outputs and inputs using agronomic (A) and economic (B) optimized N rates. Dashed lines are the desired benchmarks for high and low NUEb at 0.90 and 0.50, respectively. Solid horizontal lines are the desired minimum N output of 67 kg N ha^{-1}. The maximum Nb is indicated by the solid curve with slope 67 kg N ha^{-1}. Symbol colors indicate relative N supply-demand ratio, with low, medium, and high categories corresponding to low, medium, and high crop response to applied fertilizer. Solid colored lines represent the 50 % quantile regression for each relative yield group.

76 % (n= 225) and 67 % (n=212) of the AONR and EONR observations, respectively (Fig. 5E, F). However, most of these belonged to the 'medium' R_s group (34 % and 27 % for AONR and EONR, respectively). Overall, the comparison of RE_N with frameworks for assessing N_b and NUE_b demonstrates the existence of extremely low RE_N values enclosed in the safety ranges in both cases both falling in the 'low' R_s group (i.e., less responsive sites).

4. Discussion

4.1. Framework alignment

Appropriate frameworks for assessing NUE should incentivize management to optimize crop yields at the farm level while simultaneously meeting environmental sustainability goals (Dobermann et al., 2022; Gerten et al., 2020; Gil et al., 2019). We examined how two increasingly used indicators for reducing agricultural N losses which utilize the components of N inputs and outputs (NUE_b and N_b) compare with the historical approach of quantifying RE_N based on crop response to N fertilizer above an unfertilized control. Using a dataset of optimized N rates, we found that the majority of observations fell outside proposed thresholds for sustainable N management (Fig. 5D-F). Further investigation of relationships among agronomic (RE_N at AONR and EONR) and environmental (N_b and NUE_b) indicators revealed that relative soil N supply-crop demand contributed to the shape of yield response curve and RE_N, yet environmental indicators were unable to differentiate between sites requiring more or less fertilizer (i.e., R_s groups) and therefore did not reflect the true efficiency of N inputs (Fig. 3). This finding highlights the value of quantifying RE_N as a fertilizer-based indicator accounting for different soil N supply levels under variable conditions to improve NUE and decrease potential losses (Congreves et al., 2021; Dobermann, 2007; Ladha et al., 2020).

We are not aware of previous studies assessing the performance of N_b and NUE_b with a dataset of optimized N inputs established through field trials. It is notable that only 31–35 % of observations fell within NUE_b guidelines from the EU N Expert Panel and 37–43 % within N_b safety ranges (22 – 67 kg N ha^{-1}). This indicates that optimizing N rates alone (AONR or EONR) is not enough to minimize environmental risk based on current recommendations, resulting in reactive N leakage from agroecosystems (Bowles et al., 2018; Martinez-Feria et al., 2018). Similar tradeoffs can be expected in the other direction when frameworks are used alone – while implementing AONR or EONR may compromise environmental performance, strictly adhering to N_b or NUE_b safe operating zones will conflict with the economic objectives of farmers. Thus, efforts are needed to leverage the strengths of both frameworks to meet the objective of maximizing food production and economic returns per unit N addition while remaining within safe environmental boundaries to avoid N losses (Giller et al., 2004; Houlton et al., 2019; Schulte-Uebbing et al., 2022). Considering this, below we discuss the performance of both frameworks and subsequently explore the potential for merging RE_N with N_b to overcome their respective limitations. This new approach would help calibrate global environmental targets to local conditions by leveraging the expertise of agronomists and commonly available data for N inputs, N outputs, and crop response to applied fertilizer for different cropping systems and regions.

4.2. Options for improving NUE

A core principle of N management is matching N inputs with crop demand, with added N fertilizer supplementing, not replacing, soil N supply (Morris et al., 2018; Sawyer et al., 2006). We found that EONR was capable of improving RE_N more than AONR, but NUE_b and N_b were unrelated to RE_N because these indicators neglect the contribution of soil N supply which can vary greatly from year to year (Cassman et al., 2002). Maximum yield levels for different categories of R_s were similar for AONR, despite differences in inherent soil productivity (Fig. 4A). Because AONR is focused on determining the N rate required to achieve maximum grain yield, a weakness is recommending similar N rates regardless of indigenous soil N supply, negatively impacting RE_N in less responsive sites (Dobermann, 2007). In contrast, the EONR framework is designed to consider the relative economic value of grain yield increase per unit of added N above the unfertilized control. Thus, higher soil N supply or low R_s sites should reduce the need for external N fertilizer inputs while increasing economic gains (Bundy and Andraski, 2004). Consistent with this theory, we observed a significant relationship between higher EONR (and AONR) values and higher R_s (Fig. 4A,B), thereby improving RE_N. Yet, neither the NUE_b framework nor N_b at AONR were sensitive to changes in R_s. Thus, even when farmers are applying AONR and N_b appears to fall within sustainable ranges, it could still result in lower RE_N in less responsive sites (i.e., low R_s) which indicates a high risk for N losses. Moreover, the average trend of N_b increasing with high R_s was more prominent for EONR than ANOR (Fig. 4A, B).

The divergence in outcomes for simplified NUE indicators compared to traditional approaches in agronomy has important implications in the context of emerging policies and the urgency to address N pollution (Houlton et al., 2019; Sutton et al., 2021). A key difference of our assessment compared to previous work is that N rates were optimized, nonetheless observations occurred outside of the safe boundaries for NUE_b and N_b both at low N rates (where yields were too low or high to

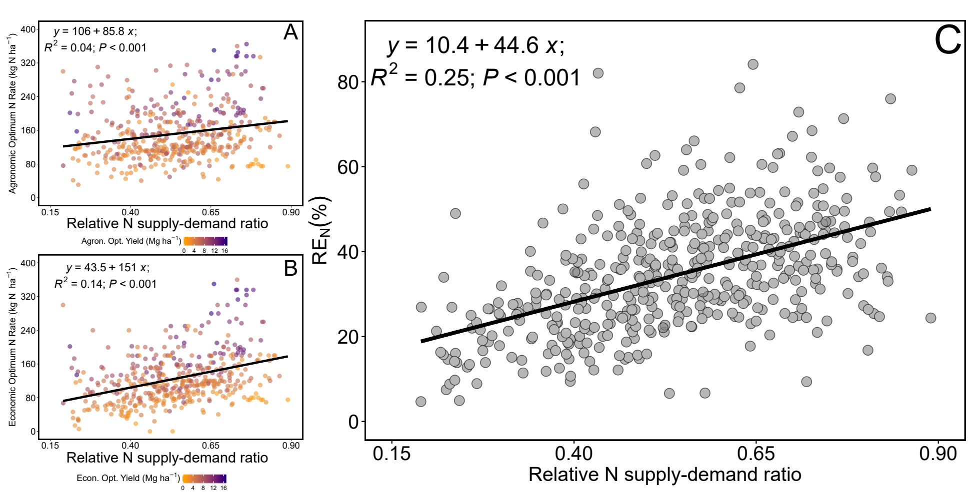

Fig. 4. Relationship between AONR (A), EONR (B), REN (C) and relative N supply-demand ratio (Rs). Color gradients in A and B represent the changes in AOY and EOY, respectively. Each point represents an individual N response curve from the dataset.

avoid excess N or soil N mining, respectively) and high N rates (generally where yields were not high enough to compensate for high N inputs). Of concern is that the occurrence of extremely low RE_N in both of these scenarios was not evident using environmental indicators because NUE_b and N_b do not account for yield responsiveness to N fertilizer and inherent soil productivity. Likewise, on the other end of the spectrum Silva et al. (2021) found NUE_b values above soil mining thresholds (>0.90) for a regional study in the Netherlands, which could be misleading in farms with a relatively small fertilizer response but high yields overall because soil N supply is still high. Thus, although NUE_b and N_b are attractive for tracking the sustainability of food production due to their simplicity and flexibility (McLellan et al., 2018; Quan et al., 2021; Tenorio et al., 2020), ignoring the contribution of R_s (which strongly influences the need for fertilizer) could have unintended consequences or even be counterproductive. For example, although lower N_b is achieved with lower R_s, this also corresponds with a significant decrease in RE_N thereby increasing the risk of N losses. Despite these observations remaining in the safe space for N_b and NUE_b, the hidden costs of low RE_N suggest the growing use of environmental frameworks deserves more attention. In this context, future policy debates must aim for a holistic approach that merges the methods of optimized N management with environmental risk, to promote benefits for both farmers and society (Tingyu et al., 2020; van Grinsven et al., 2022; Zhang et al., 2021).

It can be counterintuitive that high soil N supply relative to crop demand leads to low RE_N. However, this has been shown in other studies (Correndo et al., 2021; Cui et al., 2008; Mandrini et al., 2021; Martinez-Feria et al., 2018), where the combination of soil N supply and fertilizer N inputs provides more than sufficient N for the crop (Osterholz et al., 2017), sometimes with organic N mineralization also occurring at a higher rate than crop N uptake (Loecke et al., 2012), increasing the risk of losses. Moreover, less responsive sites can occur at high and low yield when other factors are limiting yield potential despite high N inputs. Examples of such would be sites in Sub-Saharan Africa where degraded soils are less responsive to N inputs due to limitations other than nutrients (e.g., organic matter; Vanlauwe et al., 2011), as well as more intensive, high-yielding cropping systems in Europe where only marginal responses to N inputs are observed in some regions (Silva et al., 2021). This suggests RE_N alone or other NUE metrics that include an unfertilized control (e.g., AE_N, PE_N) may serve as an environmental indicator but do not necessarily reflect optimized management under specific soil-climate conditions for a given growing season. Previous work has shown the need to improve the efficiency of N management, largely from typical farm practices (Congreves et al., 2021; Fageria and Baligar, 2005; Ladha et al., 2020; Tittonell et al., 2007). However, because the selected N rates were already optimum in this study, shifting the majority of observations towards the NUE_b safe space will either require intensification through higher crop yields ($NUE_b < 0.50$) or addressing issues of soil N mining ($NUE_b > 0.90$; Fig. 3A,B). We observed that the latter was close to the safety limits for EONR; moreover successfully identifying sites that do not require fertilizer (EONR = 0), if possible, will increase the proportion of soil N mining. This condition illustrates the challenge of optimizing N management while also meeting environmental goals related to soil N mining, as the only way to lower NUE_b below the 0.90 guideline is to apply more N fertilizer in responsive sites. However, the 0.90 guideline for NUE_b is an assumption made without soil N data, highlighting the benefit of considering soil N supply in estimating AONR and EONR, which can help determine if and when soil N mining is an issue. For example, as noted above NUE_b values above 0.90 have been reported for high yielding farms in the Netherlands, but detailed soil data is available indicating mining is generally not a concern because soil N supply is large (Silva et al., 2021).

Limiting N application in low RE_N fields will result in economic costs to the grower, but the returns to N fertilizer are much lower than under medium and high RE_N fields. In addition, the benefits to society through reduced pollution are much greater (Hill et al., 2019; Mandrini et al., 2022; van Grinsven et al., 2022). Less responsive sites usually present a wider range of slightly less profitable N rates than the AONR (i.e., flat payoff function; Pannell, 2006). For instance, in wheat trials optimum N rates within the 5 % range of profitability have shown variations of 77–51 % above and below the AONRs, respectively (Morrison et al., 1986). This relative insensitivity of profits to N rates can have important implications for sustainable N management programs in less responsive sites. The wide range of profitable N rates would provide flexibility to farmers for the adoption of mitigation practices or policies aiming to reduce N rates in low RE_N sites without incurring severe economic penalties or risks. This also suggests that recommendations stemming from agronomists should be based on profitable ranges rather than a single optimum N rate (Pannell, 2017). On the other hand, farmers may still exceed N rates above local recommendations in less responsive sites, especially if higher fertilizer costs are small compared to potential profits experienced in a good year (Rajsic and Weersink, 2008), or due to lack of access to knowledge (Huang et al., 2015) or misinformation (Sheriff, 2005). Identifying less responsive sites (regardless of the reason) can help minimize fertilizer costs to the grower, allowing them to invest in other practices and technologies to increase yield potential, while substantially reducing environmental risk associated with N pollution.

Reducing N inputs to avoid low RE_N in fields with high soil N supply relative to crop demand is a short-term alternative to mitigate N losses (Mandrini et al., 2022). Yet, in the long-term decreasing fertilizer rates below certain levels could lead to a gradual reduction of yields due to soil N depletion (ten Berge et al., 2019), whereas continuous use of N fertilizer in sites with low soil N will boost grain yields due to soil N accumulation and improvement of soil fertility (Glendining et al., 1996; Ladha et al., 2011). Our results suggest that transitioning from low to high soil N supply (high to low R_s) in the long-term would involve a higher risk of low RE_N and N_b exceeding safety boundaries (Fig. 5A). Therefore, especially for less responsive sites with high N_b or low RE_N, our findings imply that besides changes in N inputs increasing yield potential by reducing limiting factors should also be a main priority. Accordingly, crop management practices and genetics need to be adjusted towards reducing yield gaps and increasing crop yield potential to maximize the recovery of applied N fertilizer (Fischer and Connor, 2018; Giller et al., 2004). The opposite occurs for low N_b or high RE_N where farmers should ensure that N inputs can support long-term productivity by incorporating biological sources of N to improve soil fertility (e.g., cover crops, diversify crop rotations; Maaz and Pan, 2017; Macedo et al., 2022) as well as N fertilizer if yield declines are evident. Besides the temporal dimension, it is important to note that exceeding N_b safety thresholds can occur at low RE_N under low to high grain productivity levels, as well as low to high N inputs (Tenorio et al., 2020; Tittonell et al., 2008). For instance, in environments where N inputs and yield responses are generally low but attained yields are high (i.e., fertile, less responsive soils), N_b tends to be below the threshold. This is in contrast to low fertility soils where high N inputs are required to achieve relatively low yields and N_b is high. In both scenarios, N rate is optimized but other components of the cropping system must be adjusted to take advantage of added N fertilizer.

4.3. Proposed steps forward

Increasing NUE at regional and global levels is key for meeting multiple UN Sustainable Development Goals (Chang et al., 2021; Schulte-Uebbing et al., 2022). An urgent first step is getting farmers to implement cost-effective practices for optimal N management, thereby providing large environmental and social benefits (Gu et al., 2023). However, our results show that even when N rates are optimized within a given field, there are limitations to agronomic frameworks in meeting environmental goals, and in turn, limitations to environmental frameworks in identifying sites with low R_s and consequently little need for N

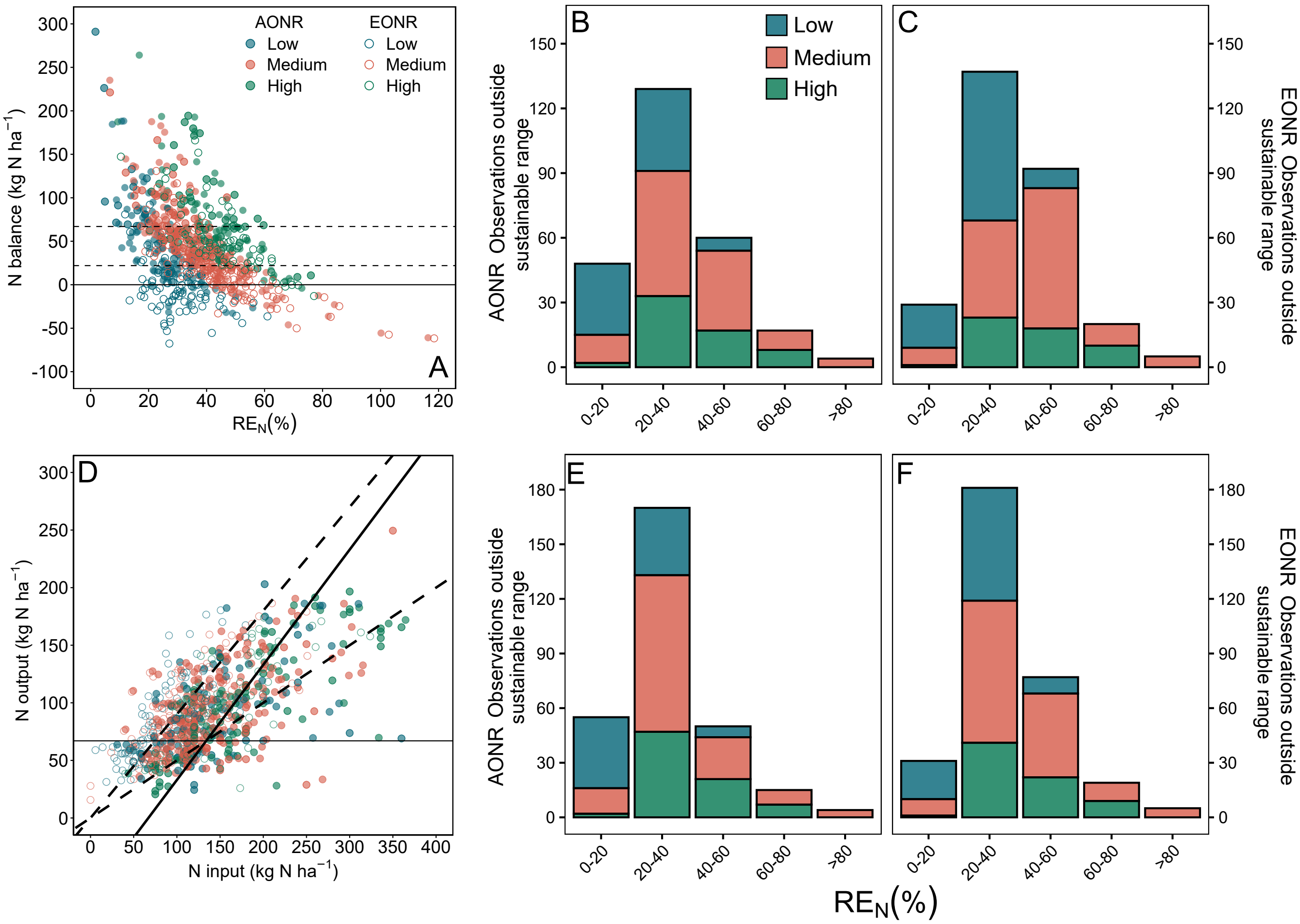

Fig. 5. Relationship between N balance (N_b) and RE_N (A) and N outputs and inputs (B) for AONR (closed circles) and EONR (open circles). Bars in B, C, E, and F, are the number of observations outside the safety boundaries of N_b (dashed lines in A) and NUE_b framework (D) for AONR (B,E) and EONR (C, F) across different ranges of RE_N (x-axis) and R_s groups (low, medium and high groups).

addition, thereby posing a risk for situations where NUE_b or N_b values may appear to be within safe boundaries but have inherently low RE_N. Thus, we propose future steps to merge insights from both frameworks based on their quantitative relationship, helping advance the long-term goal of leveraging existing data for different cropping systems and regions to develop reasonable and adaptive targets based on local expertise and environmental conditions.

Results from this study suggest the adoption of RE_N targets in combination with N_b thresholds could more comprehensively address efforts towards sustainable N management goals (Ladha et al., 2022). For instance, setting a low RE_N threshold would largely eliminate undesirable outcomes (i.e., those falling outside the sustainable N_b range), helping avoid unnecessary N fertilizer inputs in low RE_N fields (Fig. 5A-C). Our case study helps illustrate this, with 31 % of observations above the N_b threshold moving into the safe zone if agronomic N rates were reduced in fields below 40 % RE_N. Likewise, cases where RE_N was above 40 % but N_b values were below, or above thresholds represented 18 %. Another approach recently introduced consists in developing an 'environmental optimum N rate' in which the cost of N pollution to the environment, ecosystems, climate and human health is added to the economic equation of fertilizer N rate (Cai et al., 2023; Sobota et al., 2015). While prioritizing benefits for society, this approach would also help to filter less responsive sites in risk of N pollution.

A potential approach for calibrating N_b boundaries to regional RE_N based on field measurements is feasible, using available agronomic data to determine thresholds for what is locally acceptable for RE_N in terms of cropping system and yield potential. Similarly, Vanlauwe et al. (2011) proposed identifying optimum agronomic NUE across maize farming systems in Sub-Saharan Africa to develop site-specific recommendations for fertilizer use as a way to address heterogeneity (Tittonell et al., 2007). Therefore, individual growers can keep striving for optimizing economic returns like in the past, but additional steps must also be taken to adhere to N deficiency thresholds established by local experts based on achieving a minimum yield response to maintain acceptable levels of RE_N. This is necessary because in low R_s sites in the current study, economic gains still justified N fertilizer use despite extremely low RE_N, indicating large potential for N losses.

Our data illustrate that the key for achieving high RE_N is determining the magnitude of yield response to fertilizer N, which largely depends on soil N supply for the current season which often provides half or more of crop N demand (Ladha et al., 2005). Here, in 42 % of the cases soil N supply was ≥0.50 of grain N removal at AONR (i.e., B point in Fig. 2). We acknowledge that a key limitation to our study is the lack of data on other N inputs or outputs and the geographical bias. Despite including a supplementary analysis on non-fertilizer N sources (Fig. S4), lack of this information highlights the need for more field experiments and detailed measurements on N sources on N response trials. This depends on climatic conditions (Zebarth et al., 2009) and interannual variation (van Es et al., 2005) due to management practices such as residue management, cover crops, or historical fertilizer use among others. Moreover, despite the numerous methods to measure N mineralization potential, an ability to predict soil N supply it is still not sufficiently robust to be broadly utilized (St. Luce et al., 2011). Soil N stable forms can lead to less environmental losses when agronomic management aims for coupling soil carbon (C) and N cycles. In systems where N is added with C (e.g., manure, cover crops), microbial immobilization and lower mineralization rates might favor N retention in long-term soil N pools (Blesh and Drinkwater, 2013; Cao et al., 2021). Using N_b as a metric for environmental purposes could be problematic because a high positive N_b does not always correspond to a high risk of N losses, especially if surplus N is coupled with soil C as organic N in soil organic matter. Such scenarios will require detailed measurements to quantify N inputs and outputs for proper interpretation of N_b and NUE_b thresholds. The observed limitations of each framework suggest that balancing environmental and agronomic goals will require a switch in mindset from finding the optimum N rate for a field, to taking measurements that justify the need for N inputs to meet a minimum efficiency level in a growing season. Thresholds for what is deficient could be determined by field research and extension programs, not with the goal of determining how much N to apply for optimal management which is the current focus, but rather determining when a level of deficiency for unfertilized areas of the field corresponds to a certain yield or economic loss based on empirical relationships. Thus, when an unfertilized area of the field meets the deficiency criteria, this implies a low soil N supply relative to crop demand, and in turn the yield response to applied N fertilizer is expected to be large enough to satisfy the lower threshold for RE_N, helping ensure fields with optimal N inputs also remain within global environmental NUE thresholds.

Such an approach would require a shift towards in-season N management which has barriers. An increasingly important approach to determine crop N status in-season is the N nutrition index (NNI; Lemaire and Gastal, 1997). This method accounts for the N-biomass allometry in crops and quantifies the crop N status based on the concept of N dilution curves which has proven to be sufficiently robust in different crops species (Divito et al., 2016; Gastal et al., 2015; Ziadi et al., 2010), genotypes (Ciampitti et al., 2021) and management conditions (Kunrath et al., 2020). The N dilution curve provides a critical N concentration from which the magnitude of deficiency or luxury consumption can be determined if measured values are above or below that threshold (Gastal et al., 2015). By measuring the proportion of crop N demand satisfied by N supply, NNI shares similarities with the R_s metric, incorporating the co-regulation of N uptake by soil N concentration and by plant growth capacity. The consistency of critical N concentrations used for NNI calculations could overcome the limitations of approaches utilizing grain yield response curves when trying to generalize fertilizer recommendations across space and time. Instead, NNI calculation requires in-season measurement of crop N tissue and biomass that can be implemented multiple times under changing N supply conditions to identify occurrence of the deficiency and adjust fertilization strategies accordingly (Jeuffroy and Bouchard, 1999). This has been proven in multiple species and studies associating grain yield and its components to changes in NNI (Rodriguez et al., 2024; Zhao et al., 2018; Ziadi et al., 2010). In association with remote sensing tools and modeling, NNI could be deployed as a non-destructive method. For instance, association of spectral images and NNI has been reported in rice (Cao et al., 2017, 2013), wheat (Jin et al., 2015) and maize (Cilia et al., 2014).

5. Conclusions

To monitor progress towards environmental goals, simplified NUE indicators based only on N inputs and outputs are increasingly used instead of RE_N which requires additional information on crop response to N addition. However, the implications of this shift in methodology have not been critically examined. Our analysis shows that even when managing N fertilizer at agronomic or economic optimum N rates, a large proportion of observations fell outside N_b sustainability targets. Low RE_N was driven by low R_s values, yet these observations were not evident under N_b and NUE_b frameworks due to lack of sensitivity to R_s. Moreover, observations outside the safety ranges suggested the need to move towards intensification and avoiding soil N mining issues. The apparent tradeoffs suggest that a more holistic approach is necessary to address sustainable N management at the field-level. Our results highlight the need for some accounting of soil N supply (or unfertilized yields) to calibrate global NUE targets to local conditions influencing realistic RE_N values, thereby integrate the strengths of both agronomic and environmental frameworks. An important option for improving in-season management based on monitoring crop N status and adjusting fertilizer decisions accordingly is NNI. Efforts should focus on identifying less responsive sites as the controlling factor underlying low RE_N and high environmental risk. When exploring this idea in our dataset, we found that utilizing RE_N thresholds in combination with NUE_b or N_b helped address many observations falling outside safe boundaries in both environmental frameworks. Agronomists and consultants working in different crops and regions could therefore leverage available data to develop appropriate RE_N thresholds for meeting productivity objectives while providing sustainability benefits that would not be captured by the N_b or EU N Expert Panel frameworks alone. In the long-term, monitoring the relationship among soil N supply and crop demand using tools such as NNI will be required to avoid further low RE_N scenarios in fields transitioning from low to high soil fertility. Given the constraints of optimal N rates observed in our analysis, advancements in sustainable N management will demand a change in paradigm toward achieving required minimum efficiency levels to simultaneously meet agronomic and environmental goals. The adoption and future development of advanced analytical tools, machinery, and sensors will gradually alleviate current limitations for in-season N management through more accurate soil N predictions and real-time crop nutrient status.

CRediT authorship contribution statement

Cameron Mark Pittelkow: Writing – review & editing, Visualization, Supervision, Investigation, Funding acquisition, Conceptualization. **Jagdish Kumar Ladha:** Writing – review & editing, Conceptualization. **Bruce A. Linquist:** Writing – review & editing. **Fidel Maureira:** Writing – review & editing, Data curation. **Mark E. Lundy:** Writing – review & editing. **Santiago Tamagno:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Chris van Kessel:** Writing – review & editing. **Tai McClellan Maaz:** Writing – review & editing, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127231.

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