SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

DEFINING NUTRIENT USE EFFICIENCY IN RESPONSIBLE PLANT NUTRITION

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KEY POINTS

- **Nutrient use efficiency indicators are important for sustainability and efficiency assessment in farming.**
- **Different indicators, with various combinations of nutrient outputs and inputs, are required to quantify nutrient use efficiency in relation to the multiple aims of responsible plant nutrition.**
- **Comprehensive assessment of sustainable crop production requires additional indicators.**

Discussions on sustainability often focus on improving resource use efficiency. Efficiency is generally a ratio of outputs to inputs, with higher ratios implying less waste. Minimizing waste leads to lower costs of production, smaller losses to the environment, and less depletion of non-renewable resources. In this context, improving nutrient use efficiency (NUE)[1] is of critical importance to global food security and protecting the environment *(1)*.

Estimates of NUE in cropping systems range widely. Besides differences in farming practices and environments, such differences can often be attributed to the multitude of indicators used to quantify NUE. Hence, when interpreting published values, it is important to consider which indicator was used and how it was calculated. In this issue brief we aim to clarify terms, formulas, and definitions of widely used NUE indicators, to guide in their interpretation, and to link them to the five aims of responsible plant nutrition *(2)*.

We recommend that the default use of the term NUE is in reference to the ratio of nutrient outputs to inputs in a partial nutrient balance for an agricultural cropping system. We also provide standardized names and abbreviations for other formulations of NUE indicators that focus on fertilizer use, crop performance, or systems larger than cropping systems. While use efficiencies often focus on nitrogen (N) and phosphorus (P), the concepts described apply to any nutrient.

NUE INDICATORS FOR DIFFERENT SYSTEMS

When analyzing efficiency of nutrient use in agricultural production, the considered systems, inputs, and outputs vary widely. This can result in a multitude of NUE indicators, with each requiring a specific interpretation.

Variation of the system. Indicators may differ depending on the agricultural system for which nutrient flows are quantified. Systems may differ in spatial scale (e.g., field, farm, country, the globe), boundaries (e.g., soil surface, farm gate, parts or all of the food supply chain), and temporal scale (e.g., single crop season, whole year, or multi-year crop rotation) *(3)*. A cropping system with a soil surface boundary is shown in Figure 1. The cropping system is central to a much larger agri-food system and value chain and also the location where most of the world's mineral fertilizers are applied.

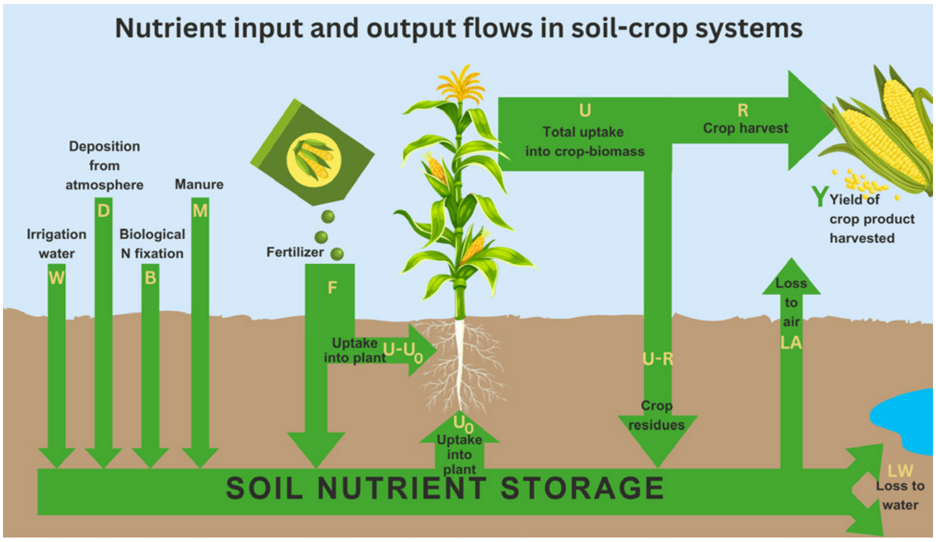

Figure 1. Generalized nutrient flows into and out of a soil-crop system. W = Irrigation water; D = Deposition from the atmosphere; B = Biological nitrogen fixation; M = Manure applied; F = Fertilizer applied; U = Uptake of nutrient by the crop in above-ground biomass; R = Removal or "offtake" of nutrient in the harvested crop product; U-R = Nutrients returned to the field as crop residue; U_0 = Crop nutrient uptake from soil and other indigenous sources; U-U_0 = Crop nutrient uptake associated with fertilizer application; LA = Nutrient loss to air (as gases such as NH_3 or N_2O); LW = Nutrient loss to water (by leaching, runoff, and erosion); Y = Crop yield; Y_0 = Crop yield without nutrient applied (not shown).

1. In this paper we frequently use the term "nutrient use efficiency (NUE)" with a broader meaning. For more precise definitions of different forms of NUE indicators see Table 1.

Variation of the output. For crops, outputs used in NUE calculation may include 1) the mass and nutrient content of the harvested crop product, or the whole above ground crop biomass, or 2) the additional nutrient uptake due to nutrients added from fertilizer. More rarely, some formulations of NUE may also include added nutrients that are retained in the soil, since these nutrients may build up soil fertility and improve soil health. Nutrient losses to air or water, however, are often not considered outputs as they represent 'nutrient waste.'

Variation of the input. A wide range of nutrient inputs to the system can be considered in NUE indicator definitions: fertilizer, manure, irrigation water, deposition from air, and biological N fixation. Nutrients supplied to the crop from the soil also comprise a substantial proportion of crop uptake, but in soil surface or farm-gate systems, nutrients from soil are considered an indigenous resource.

As a result of these variations, hundreds of possible ratios of outputs to inputs could be calculated and applied to systems that vary in boundaries, and spatial and temporal scales. Many NUE indicators have been reported: 18 were described in detail for N fertilizer efficiency in cereal production *(4)* and 23 in a recent paper on definitions of N use efficiency for today and tomorrow *(5)*. Each can be useful for a specific purpose. But only some are sufficiently comprehensive as indicators for the sustainability performance of cropping systems and for practical management decisions on-farm.

The choice of NUE indicators also needs to consider how easily and reliably the components can be measured or estimated, and whether the indicator can be interpreted for purposes of guiding farmers' nutrient management, business or policy making. Farmers typically know the amounts of fertilizer purchased, crop yields and sometimes the protein content of the crops that are sold. Many other outputs (e.g., crops consumed on-farm) or inputs (e.g., manure, atmospheric deposition, biological N fixation, nutrients in irrigation water) are not routinely available.

The soil-crop system in Figure 1 shows the major nutrient flows that comprise the terms of major NUE indicators. Different inputs may follow different pathways of entry, some to the soil and some more directly to the crop. Their fates also differ; of the nutrients taken up into the crop, some are removed with the harvest and some returned to the soil as crop residues. Some nutrient inputs are not taken up by the crop, but may be cycled within soil organisms, or build up in the soil, or be lost to air or water through various processes.

RECOMMENDED INDICATORS

In Table 1 we define nine NUE indicators that, in our view, are most useful for assessing agricultural systems in terms of the multiple goals of responsible plant nutrition. The first group focuses on indicators of fertilizer use efficiency, the second group on the crop, and the third on the nutrient balance in a defined system with multiple sources of nutrient inputs in addition to fertilizers. Names of each indicator have been standardized to the possible extent, but the terminology is not always used consistently in the literature. We generally recommend reviewing the underlying data and calculations in detail before drawing conclusions about any reported values of NUE.

Table 1 also provides examples of reported or typical values of the different NUE indicators. Note that even for consistently defined formulations, the range of values is broad. Much of this variation arises from factors beyond the control of the farmer, including weather impacting crop growth and soil processes.

It should also be kept in mind that many of the indicators shown in Table 1 are interrelated. For example, cereal crops with good management often have the following characteristics in terms of N use efficiency: a partial factor productivity (PFP) of >60 kg grain/kg N applied, an agronomic use efficiency (AE) of 25 kg grain/kg N applied, a fertilizer recovery efficiency (RE) of >50%, a physiological efficiency (PE) of >50 kg grain/kg N taken up from fertilizer, and an internal efficiency (IE) of >60 kg grain/kg N taken up from all sources *(6)*. In such cases, the N surplus (risk of N losses) is low, resulting in a high system-level N use efficiency (NUE_{PB} in Table 1) of 70% or more.

FERTILIZER INDICATORS

In most crop production systems, fertilizers comprise the majority of nutrient input, making their use efficiency a focal point. The three main indicators specific to applied fertilizers are: partial factor productivity, agronomic efficiency, and recovery efficiency. These indicators presume the soil surface as the system boundary, which is appropriate for farms producing mainly crops. These indicators can also be used for organic fertilizer inputs such as manures, biosolids, or composts. Nutrients from these sources may be released slowly over the course of several growing seasons. Hence, their efficiencies calculated on the basis of a single growing season may underestimate their longer-term NUE.

Partial factor productivity (PFP) is the ratio of crop yield harvested per unit of nutrient applied (Table 1). It is useful for comparing fields growing the same crop, both within one farm and among farms, but it can also be used to analyze trends over time at farm, national, regional or even global scales. Each crop product has its own standard for trade moisture, and inclusion or exclusion of husks, so comparing across crops does not relate well to nutrient management.

At the farm level, PFP provides a relative comparison of crop product output to fertilizer input and is calculated from information readily at hand. For farmers, it is a robust and economically meaningful indicator. High indigenous soil nutrient supply and high fertilizer use efficiency are equally important for achieving a good PFP level. In well-managed cereal crops, for example, PFP usually ranges from 50 to 100 kg grain per kg N applied. At low fertilizer rates, when crop nutrient output is derived mostly from indigenous soil nutrient supply, PFP may be higher than this range, and may indicate soil nutrient mining that can lead to decreased crop yield in future growing seasons. PFP declines rapidly when nutrient application rates are increased from low levels.

Agronomic efficiency (AE) is similar to PFP but focuses on the yield increase attributed to the nutrient input from fertilizer. It is the product of recovery efficiency (RE) and physiological efficiency (PE) and thus depends on many agronomic management practices that determine a healthy crop *(6)*. Generally speaking, AE is considerably lower than PFP because PFP includes the yield derived from nutrients supplied by the soil and from fertilizer. Using N as an example, in well-managed cereal systems AE is commonly about 20-30 kg grain per kg N applied, but it can also be larger than that.

To measure AE, the yield from an unfertilized check plot (Y_0) is required. Check plot yield is barely ever available on-farm, because farmers are reluctant to omit fertilizer application on a field strip. Nevertheless, at the farm level, AE provides an important basis for calculating the first-year contribution to profit from the use of fertilizers. Knowing achievable AE values can also be useful at the farm level to estimate fertilizer rates required to raise crop yields to attainable levels. Since AE focuses on the yield gain induced by the fertilizer alone (i.e. difference between Y and Y_0), AE is more sensitive to nutrient application practices than PFP, including timing and placement as well as choice of fertilizer source. It declines less than PFP as rates of application increase to an optimum level. However, when surpassing the optimum, the decline is more rapid.

Table 1. Nutrient use efficiency (NUE) indicators relevant for sustainable crop production.

NUE indicator	Calculation†	What it represents	Examples of reported values	
		Fertilizer indicators		
PFP Partial factor productivity	= Y/F	Yield of crop harvested per unit of fertilizer nutrient applied.	Global averages for 2017-2019, based on fertilizer use by crops estimates *(7)* and FAO crop yield statistics. N in cereals *(6)*	Maize: 52 kg/kg N; 323 kg/kg P Wheat: 38 kg/kg N; 266 kg/kg P Rice: 43 kg/kg N; 293 kg/kg P 40-80 kg/kg N
AE Agronomic efficiency	= $(Y-Y_0)/F$	Increase in yield per unit of nutrient applied, in response to the application of the nutrient.	N in cereals *(6)* N fertilizer in sub-Saharan African maize *(8)* P fertilizer in Asian rice, wheat, and maize *(6)*	10-30 kg/kg N 19-39 kg/kg N 20- >50 kg/kg P
RE Recovery efficiency	= $(U-U_0)/F$	Increase in nutrient in above ground crop biomass per unit applied, in response to application of the nutrient.	N in cereals *(9, 10)* N in irrigated maize after maize or soybean *(11)* P in Asian rice, wheat, and maize *(6)*	18-56% 67-75% 10-35%
		Crop indicators		
IE Internal efficiency	= Y/U	Crop yield per unit of nutrient uptake in above-ground crop biomass.	N in cereals *(6)*	30-90 kg/kg N
PE Physiological efficiency of applied nutrient	= $(Y-Y_0)/(U-U_0)$	Crop yield increase in response to increase in nutrient uptake in above-ground crop biomass.	N in cereals *(6)*	40-60 kg/kg N
NHI Nutrient harvest index	= R/U	Nutrient in harvested crop product per unit of nutrient in above-ground crop biomass.	N in maize *(12–14)*	58-81%
NC Nutrient concentration	= R/Y	Nutrient in harvested crop product per unit of yield.	N in maize *(12, 13)*	1.1-1.5%
		System indicators		
NUE_{PB} Nutrient use efficiency based on soil surface outputs and inputs (partial balance)	= R/(F+M+B+D)	Nutrient removed in harvested crop product per unit nutrient input from different sources	Global cropland in 2020 (15)[2] All countries USA India Ghana	 N 55%, P 77%, K 80% N 71%, P 110%, K 91% N 39%, P 57%, K 110% N 108%, P 430%, K 286%
NUE_{FG} Nutrient use efficiency based on farm gate outputs and inputs	= Exported products/ (Imported feed+F+M+ B+D+W)	Nutrient in products leaving the farm per unit of nutrient entering the farm	Farms in Europe *(16)* ‡ Arable farms Dairy farms Pig farms	 45-75% 21-38% 37-51%

† See Figure 1 for definition of the terms in the calculation formulas.
‡ Interquartile range.

2. For other countries, trends over time, inputs and outputs see https://www.fao.org/faostat/en/#data/ESB

Recovery efficiency (RE) uses the same approach as AE but considers the increased nutrients in the above ground crop biomass[3] in response to nutrient application. However, supplied nutrients can be exchanged with the indigenous nutrients in the soil, so that the nutrient increase may not be due to the actual molecules of the supplied nutrients from the fertilizer. It is assumed that the uptake of nutrient in the unfertilized check plot (U_0) represents what the soil supplies to the fertilized crop. This assumption is subject to some error since the fertilized and unfertilized crops may not take up the same amount of soil nutrient. Instead, deficient plants often induce the expression of specific nutrient uptake systems (17). Also the addition of nutrients may affect release of indigenous soil nutrients (9). Nevertheless, RE is assumed to reflect the quantity of the nutrient 'used' by the plant in the enhancement of yield, thus estimating the apparent recovery of fertilizer.

Like AE, the RE requires an unfertilized check plot. In addition, it requires the measurement of crop biomass and its nutrient content. It is thus even more difficult to measure in practical farming than AE, and global assessments have often been based on relatively few and outdated measurements. Very little new data on RE have been published in recent decades (18). Averages for RE of applied fertilizer N were reported in various regions within different countries. Recent studies assumed average values of 56% for maize, 36% for rice, and 48% for wheat in production fields (10). In well-managed irrigated maize crops, however, the RE of N fertilizer can reach 75% or more (11). Crop genetic improvement for yield has also contributed to increasing RE of applied N. The genetic potential for the RE of N in maize has improved substantially, from 38% for older cultivars to 59% in newer hybrids (12).

The RE of P tends to be lower than that of N (6), but also varies widely. A recent literature summary (19) found an average RE of applied P fertilizer in cereal crops of just 12%, which was lower in maize than in rice and wheat, and lowest in soil with a near neutral pH. Yet, this study included a considerable number of soils with high levels of available P, which likely contributed to the low RE values for P in maize.

Interpreting RE values requires care as low RE values of a nutrient can arise for two different reasons. First, plants may have poor access to added fertilizer due to other soil or plant constraints (e.g. salinity, acidity, drought, disease), another nutrient deficiency, fixation or tie-up in the soil, or poor placement or timing. Second, low values can also indicate that nutrient availability in the soil is already high, and that plants no longer need the extra nutrient supplied as fertilizer. Practices to improve RE include the timing and placement of fertilizer applications to match crop uptake patterns and to avoid losses, as well as the choice of fertilizer source to suit the soil conditions. The selection of crop cultivars with more effective root systems and higher yields also improves RE. Crop management practices that increase yield, including irrigation, can improve RE.

RE is sometimes also calculated by applying a labeled fertilizer, which is enriched in an isotope (most commonly ^{15}N for N and ^{32}P or ^{33}P for P). The fraction of the isotope in the plant is then compared to that in the fertilizer. This method of calculating RE requires small controlled experimental plots and the analysis of the harvested material for the isotope. It is subject to confounding by nutrient cycling and substitution among various pools of organic and mineral nutrients in the soil (9). Measured in a single crop season, it fails to account for the uptake of the labeled nutrient by subsequent crops. Generally, RE calculated in this way is smaller than that calculated by difference of $U-U_0$. The average RE of applied fertilizer N in grain crops was reported as 39% when calculated from isotope tracers, as compared to 48% when calculated as the difference between U and U_0 (20). An isotope recovery study at seven sites in Australia found that RE of P fertilizer applied to wheat ranged from 3 to 30%, increasing with rainfall (21). Isotope labels are more useful for tracing multiple fates of applied nutrients than for determining a value of NUE that assesses the sustainability of cropping systems (22).

RE has also been estimated as the difference in nutrient content of the harvested portion removed in crop harvest in response to applied nutrient (23). Interpreting this figure is difficult as it ignores how the nutrients of the current crop's residues contribute to the next crop, since part of it comes from the fertilizer applied to the current crop. It also can relate poorly to N loss to the environment (24).

CROP INDICATORS

The crop indicators reflect how nutrients taken up by the crop are allocated between harvested portions and crop residues, and how they contribute to increasing crop yield or quality.

Internal efficiency (IE) reflects the ability of a plant to transform nutrients acquired from all sources (soil, fertilizer) into economic yield. This indicator depends on a plant's genotype, environment, and management. Low IE suggests that the plant converts internal nutrients poorly due to stresses, such as other nutrient deficiencies, drought, heat, toxicities, diseases or pests, particularly during the later part of the growing season. Genetic improvement plays a significant role too, particularly in terms of increasing sink size and harvest index of crops. For example, maize breeding increased IE of nitrogen from 45 per kg of N taken up in 1946 to 66 kg/kg in 2015 *(12)*.

Physiological efficiency (PE) reflects the ability of a plant to transform nutrients acquired from fertilizer into economic yield (grain). This indicator also depends on a plant's genotype, environment, and management. Low PE suggests a sub-optimal growth arising from nutrient deficiencies, drought stress, heat stress, mineral toxicities, or pests.

Nutrient harvest index (NHI) reflects the allocation of nutrients to the harvested portion relative to the total aboveground biomass of a crop. The NHI thus expresses the amount of nutrient that can contribute to nutrition in foods and feeds as harvested crop products, as well as the amount of nutrient returned to the soil as crop residues. Common ranges of NHI have been reported as 59-70% for N, 79-91% for P and 13-19% for K in maize *(13)*, or 54-65% for N, 61-71% for P and 12-19% for K in rice *(25)*. In other words, for most cereals, the NHI of N and P exceeds 50 or 60%, while the NHI of K is mostly only 20% or less. Genetic improvement has led to significant increases of NHI in many crops. Semi-dwarf cultivars of wheat and rice developed during the Green Revolution also have higher NHI than traditional varieties. In maize, breeding in North America led to an increase of the NHI of nitrogen from 58% in 1946 to 81% in 2015 *(12)*.

Nutrient concentration (NC), while not commonly considered an expression of nutrient use efficiency, is the ratio of a particular nutrient in a harvested crop product to the crop's total mass. NC may be influenced by changes in NUE, particularly IE, PE and NHI. It is particularly important

3. Application of fertilizer also increases nutrient uptake into the below-ground biomass, including roots, as well as the above-ground, but since this is difficult to measure it is usually ignored, except in the case of crops like groundnuts or potatoes, harvested for their below-ground portions.

for nutrients with specific end use requirements, such as crude protein which is measured as total N. Average values and ranges of NC for many crops are provided in Ludemann et al. *(26)*. Common ranges for NC have been reported as 1.2-1.5% for N in maize *(13)* and 1.0-1.3% for N in rice *(25)*. A decline in maize grain N from 1.4% to 1.1% appears to have been associated with decades of breeding *(12)*.

SYSTEM INDICATORS

System indicators are generally more comprehensive and provide evidence as to whether a system (field, farm, other scale) is likely to gain or lose nutrients, i.e. whether the nutrient balance is positive ('surplus') or negative ('deficit'). In cropping systems this requires quantifying multiple inputs in addition to a fertilizer (Figure 1), such as manure or other organic materials, atmospheric deposition, irrigation water, seeds, and biological fixation (in the case of N). On the other hand, nutrient outputs as harvested product are usually known and no comparison to an unfertilized control is needed.

Nutrient use efficiency expressed as partial nutrient balance ratio (NUE_{PB}) is the formulation most commonly referred to as NUE (3). We recommend its use for most soil surface nutrient balances, which may range from field (16) to national or global scales (15). The term 'partial' refers to the fact that only harvested outputs are included, not nutrient losses or changes to soil nutrient storage (Table 1). Normally, all important inputs should be included in the denominator. In practice, the inputs included vary considerably among studies, since some inputs can be assumed to be small, and some are not measured. In a nutrient budget for potatoes, for example, the seeds may contain substantial amounts of N and K, making it important to include seed input in the denominator. Biological fixation of N is generally small for most cereals (<10 kg N per ha) but can be higher for rice and sugarcane (15-30 kg N per ha) and even much higher (100-300 kg N per ha) for legumes such as soybeans, groundnuts, pulses, and forage legumes. Input of nutrients through irrigation water can be important under certain conditions. Calculating the NUE_{PB} requires measuring or estimating the nutrient content of the harvested crop product (NC). For some crops, such as bread wheat, for which a protein premium may be paid, attributes such as grain N may be measured, and even mapped out within-field using on-the-go infrared analysis. For others, tables of representative values (26) or prediction models (27) can be used. In any case, it is important to compare the actual formula before interpreting or comparing values of NUE_{PB}.

Averaged across global cropland, and including fertilizer, manure, biological fixation, and atmospheric deposition as inputs, NUE_{PB} has increased in recent decades to 55% for N and 77% for P (Table 1). Estimates of NUE_{PB} often differ, owing to differences in data sources, coefficients used and the items considered as inputs. For example, previously published estimates of global crop NUE_{PB} of N in 2010 ranged from 40% to 53% (28). Country-specific examples in Table 1 illustrate how the NUE_{PB} varies widely among countries. High NUE_{PB} levels are the result of managing crops to achieve high yield levels, and ensuring that all sources of nutrient input are accounted for when making decisions on the rates of fertilizer application. Ensuring that fertilizer source, timing, and placement are appropriate for the soil and cropping system also improves NUE_{PB}.

Nutrient use efficiency expressed as farm-gate nutrient balance ratio (NUE_{FG}) describes a larger system than the soil surface. Many farms integrate crop production with growing animals, poultry, fish, etc. Defining the farm gate as the boundary allows for the inclusion of these other components, and simplifies some of the calculations. Some inputs, such as manures, are internally cycled and do not need to be considered, even thoughthe result reflects their management. NUE_{FG} requires accounting for all nutrients entering and exiting the farm. Inclusion of livestock tends to reduce NUE_{FG} in comparison to NUE_{PB} as it introduces an additional trophic level. Improving NUE_{FG} requires integrating crops and other factors to optimize nutrient utilization on the whole farm. This includes managing both manure to minimize nutrient losses and feed crops to minimize the need for external nutrient input (29).

A further expansion of the system boundary leads to the concept of food chain nutrient use efficiency (NUE_{FC}), defined as the ratio of nutrient available for human consumption to the newly fixed and imported nutrient input to the whole food system (30). For N, the NUE_{FC} has been estimated to range from 10% to 40% among countries in Europe between 1980 and 2011 (30). However, because NUE_{FC} addresses a very large and complex chain of production, it is difficult to assess meaningfully, or use for practical purposes.

CONNECTING TO THE FIVE AIMS OF RESPONSIBLE PLANT NUTRITION

Responsible plant nutrition encompasses a broad array of scientific and engineering know-how, technologies, agronomic practices, business models, and policies that directly or indirectly affect the production, utilization, and recycling of mineral nutrients in agri-food systems *(2)*. The five aims of the new paradigm for plant nutrition expand the traditional focus on income, productivity, efficiency, and resilience of farmers to address needs for increased recycling, improved soil health, enhanced human nutrition, and reduced emissions related to greenhouse gases, pollution, and biodiversity. Relevance of specific indicators of NUE to each of these five aims is outlined in Table 2 and discussed further here.

Table 2. Indicators of NUE relevant to the five aims of responsible plant nutrition.

AIM	SCALE	RELEVANT NUE INDICATORS†	USES
1. Improve income, productivity, efficiency & resilience of farmers	Field and farm, scalable	PFP	Evaluate efficiency performance. Assess crop production practices on-farm.
		AE	Evaluate return to fertilizer expense.
		NUE_{PB}	Evaluate performance. Identify need to reduce or increase nutrient input.
	Field plot, extrapolated to larger region	AE, RE, IE, PE	Assess crop ability to take up nutrients from applied fertilizers in agronomic research and crop genetic improvement.
2. Increase nutrient recovery & recycling from waste	Farm gate	NUE_{FG}	Compare nutrient outputs to inputs on farms.
	Field plot, extrapolated to region	AE, RE	Assess quantity of nutrient potentially available from nutrient sources derived from wastes.
3. Lift & sustain soil health, including soil carbon	Field and farm, scalable	NUE_{PB}	Assess potential for change in soil nutrient storage (deficits leading to mining, surpluses leading to excess accumulation).
		NHI	Assess quantity of nutrient input to the soil from crop residues (high NHI means less nutrient returned to soil).
4. Enhance human health through nutrition-sensitive agriculture	Field and farm, scalable	NC	Assessment of nutritional quality of foods and feeds produced.
		NHI	Assess nutrient transfer to harvested product.
5. Minimize GHG emissions, nutrient pollution, & biodiversity loss	Field and farm, scalable to regional cropping systems	NUE_{PB}	Assess potential for nutrient losses arising from crop nutrition practices.
		RE	Assess potential nutrient losses due to inefficient fertilizer use

† as defined in Table 1.

1. The aim of improving income and efficiency of crop producers can be informed by PFP, AE and NUE_{PB} at the field or farm-scale (Table 2), against established benchmarks as well as over time. By tracking PFP, a farmer can evaluate how soil quality and production practices that include source, rate, timing and placement of fertilizer applications, as well as tillage, planting dates and methods, cultivar selection, and other practices impact on the amount of crop harvested per unit of fertilizer applied. While requiring more effort, tracking AE provides a more direct measure of the additional crop harvested in response to the use of fertilizer, and with price information, the economic return to fertilizer use. Tracking NUE_{PB} enables adjusting nutrient input amounts to meet high productivity, efficiency and environmental standards. Additionally, mainly for researchers, tracking AE, RE, IE, and PE in field plots research helps verify efficacy of practices and identify the mechanisms by which they influence NUE.

   In several countries with improving productivity trends in cereal crops, PFP has increased simultaneously with yield over the past few decades (31). This change has been driven not only by changes in fertilizer management, but by improvements in agronomic practices and crop genetics, supported by large public and private investments in research and innovation. Such sustainable intensification can continue, but requires continued and increasing support for research and appropriate policies and institutions (32). Nevertheless, it must be kept in mind that increasing NUE per se will not necessarily increase crop productivity. The various NUE indicators tend to decline with increasing nutrient input, whereas in situations of low nutrient inputs, a high NUE may be associated with both a very low crop yield and nutrient depletion in the soil. Therefore, NUE, no matter in what form, should be interpreted in the context of other indicators of crop productivity.

2. The aim of increasing nutrient recovery and recycling can be informed by farm-gate NUE_{FG} and nutrient surplus (Table 2). If NUE_{FG} is low, it raises questions as to where on the farm nutrients are being lost or accumulated, and how these flow paths could be managed better to direct more of the available nutrients to the crop. Better manure storage and application equipment, for example, can increase NUE_{FG} by

meeting more of the crop's nutrient needs with manure, allowing fertilizer inputs to be reduced. A high NUE_{FG} indicates net nutrient export from the farm. In this case, fertilizer or nutrients derived from wastes (including manures, composts, biosolids, etc.) can be imported to the farm and beneficially used. Indicators such as AE or RE may be useful in assessing the availability of nutrients in sources derived from wastes.

3. The aim of improving and sustaining soil health, including soil organic carbon, is informed by NUE_{PB}. Maintaining soil fertility requires a nutrient input level that balances crop removal. When more nutrient is harvested than applied, mining from soil reserves is likely, depleting soil fertility (soil nutrient storage as shown in Figure 1). The optimum level of nutrient use efficiency depends on the current level of the nutrient in the soil. For soils with very high levels of available nutrients, such as P and K, deficit nutrient balances may be appropriate for defined periods of time in order to reduce losses that may risk harm to the environment, and for optimizing NUE and the economics of production. It is important, however, to monitor the drawdown of soil nutrient resources and adjust input rates accordingly. For soil organic matter to increase, a surplus of the nutrients that comprise stabilized soil organic matter is required. Additions of N, P, and S fertilizers increase humification efficiency and soil carbon sequestration, as shown in an annually cropped wheat and canola field study over 5 years in Australia *(33)*. Rates of N that were surplus to the needs of maize promoted additional carbon capture by a rye cover crop in the cropping system, increasing the sequestration of carbon in the soil *(34)*. The harvest index of a crop, and its NHI, can also be important as they reflect the nutrient composition of the crop residues returned to the soil. Ratios of carbon to nitrogen in the crop residues can be particularly important *(34, 35)*.

4. The aim of enhancing human health through nutrition-sensitive agriculture requires due attention to NC and NHI. NHI tends to correlate positively with other formulations of NUE, while NC generally correlates negatively. For some end uses, like maize grown for grain feed, carbohydrates (energy) are the most desired attributes of the end product, and protein may matter less. Nevertheless, for many crops, higher levels of protein or mineral nutrient concentrations—particularly those of zinc—may be desired. These trade-offs need to be monitored and evaluated when other NUE indicators change.

5. The aim to minimize nutrient pollution in all its forms can be evaluated using indicators such as NUE_{PB} and RE. Generally, higher values are associated with lower prospects of nutrient losses to air and water (Figure 1). Commonly, excessive nutrient surpluses (= low NUE_{PB}) or low RE indicate a high risk of environmental harms: nitrate loss to groundwater, nitrous oxide and ammonia loss to the air, and eutrophication of freshwater and marine waters due to N and P losses in runoff, erosion, and drainage water. Some losses, such as dinitrogen emission to the air, do not cause direct harm. Nevertheless, they are wasteful in terms of the resources consumed and the environmental impacts of producing and transporting the nutrient inputs. A focus on improving NUE_{PB} to reduce nutrient surplus simultaneously reduces losses in all of these nutrient impact pathways *(36)*.

   In certain situations, however, a nutrient surplus represented by NUE_{PB} values considerably below 100% may be beneficial rather than harmful. For example, in acid, P-fixing soils of the tropics, large P surpluses may initially be needed to optimize plant-available soil P-levels *(37)*. Likewise, the cumulative P-surplus in Brazil provides value for sustaining future productivity *(38)*. Another interesting observation is that surplus N from cropland may, through atmospheric re-deposition, relieve limitations to forest productivity and improve resilience and carbon sequestration *(39, 40)*.

Transitions toward responsible plant nutrition involve synergies and trade-offs among the five aims. The diverse formulations of NUE indicators relevant to each help quantify these synergies and trade-offs, facilitating stakeholder input. While many other considerations apply to quantifying the progress towards each of these five aims, the NUE indicators outlined above can play important roles.

FULL ASSESSMENT REQUIRES THE INTEGRATION OF DIFFERENT INDICATORS

While the individual indicators discussed above are all useful to evaluate specific outcomes of responsible plant nutrition and 4R Nutrient Stewardship *(41)*, not all can be applied to every situation, and potential trade-offs may occur. For proper interpretation and use, it is therefore desirable to asses NUE in conjunction with desirable productivity and environmental targets. Two approaches for this are the Safe Operating Space and the Sustainable Nitrogen Management Index.

SAFE OPERATING SPACE

It has been proposed that that NUE defined as the ratio of nutrient yield in harvested crops to nutrient inputs (NUE_{PB} in Table 1), along with nutrient yield (R) and nutrient surplus (calculated as R minus I, see Fig. 1), can be used to define a safe operating space for responsible crop nutrition (42, 43). This space is defined by:

1. an acceptable range of NUE, since high levels risk mining soil nutrients, whereas low levels waste fertilizer and other resources
2. a minimum acceptable level of productivity to meet human need for agricultural products
3. a maximum acceptable level of nutrient surplus to minimize nutrient losses and pollution.

The threshold levels defining this space differ among cropping or farming systems. They may also reflect local resource constraints, stakeholder values, or policy objectives.

To illustrate this further, a possible safe operating space for N in global croplands is shown in Figure 2 as an example,

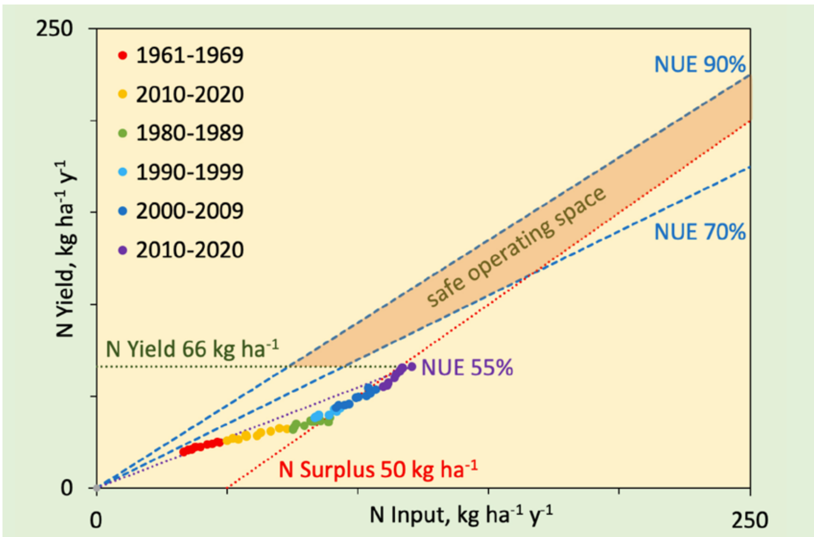

Figure 2. Progress towards reaching a safe operating space for global cropland nitrogen use, 1961 to 2020. The desirable window of N use efficiency (calculated as NUE_{PB}) is shown by the dashed blue lines (70-90%). The dotted red line depicts a maximum acceptable N surplus of 50 kg per ha, calculated by dividing the planetary boundary for surplus N (1) by the global area of cropland. The dotted horizontal line (green) represents a current crop productivity level of 66 kg N per ha per year, which would rise further as food demand increases in the future. Data from the global cropland N balance (15).

where N output, N surplus and N use efficiency are related to N input. The upper limit for NUE_{PB} of 90% was suggested to avoid the risk of mining soil N stocks by depleting soil carbon (42), whereas a lower NUE_{PB} limit of 70% represents a target for improving N use efficiency at a global scale that is aligned with environmental needs (44). In global crop production, yield of N per hectare has increased since 1961, and N use efficiency since the 1990s. Hence, after decades of slow progress, average global cropland N use efficiency (NUE_{PB}) has started to move closer to the safe operating space (Figure 2), but more efforts are needed to reach the level necessary for achieving future food production and environmental goals. As yields continue to rise, however, so will the minimum NUE required to avoid exceeding a given limit for N surplus. Considerably improvement to NUE is required to move crop production into the safe operating space.

The safe operating space approach represented in Figure 2 is applicable at any scale, from field to globe, because values are per unit area. However, regional boundaries and thresholds are more appropriate than global ones (45) because they better take into account regional differences in the current status of N use as well as differences in farming in general. It should be noted that the safe operating space concept also has a few drawbacks. The assumption that productivity can be equated with N yield may be questionable for certain crops grown for non-energy or non-protein purposes (e.g. coffee, cacao). There is no specific measure of soil nutrient depletion and also no accounting for nutrients needed for soil carbon sequestration or other soil health improvement objectives. For those not familiar with NUE concepts, Figure 2 is difficult to interpret and provides no single numeric score.

SUSTAINABLE NITROGEN MANAGEMENT INDEX

Another approach to balancing NUE with productivity is the Sustainable Nitrogen Management Index (SNMI), calculated as *(46)*:

$$SNMI = \sqrt{(1 - R^*)^2 + (1 - NUE)^2}$$

where R* is removal or "offtake" of nutrient in the harvested crop product (R) divided by a global target productivity in terms of N yield, and other adjustments are made for cases where $NUE_{PB}>1$. Mainly, the SNMI approach combines productivity and NUE_{PB} into a single numeric value that captures the progress toward both increasing productivity benefits for crop production and decreasing detriments associated with N losses. Its optimum value is as close to zero as possible. It could also be modified as a measure of indexed productivity, rather than R, for crops whose productivity is not represented by N yield (in fact, productivity could be indexed for quality as well as quantity). As shown in Figure 3, however, equal values can be obtained for situations of high productivity and low NUE as for those with low productivity and high NUE. In fact, China, Canada, and Ghana—three countries differing radically in productivity and NUE—are placed in the same class. Thus, the SNMI requires disaggregation into its components to balance this trade-off. The SNMI approach also does not explicitly identify situations where soil health may be degraded by nutrient mining.

The SNMI indicator has been used in complex indicator systems for Sustainable Development Goals (SDGs), where a single indicator is needed to monitor the progress of agriculture sustainability. It has been adopted in the Environmental Performance Index *(47)*, and in the SDGs Index and Dashboard *(48)*.

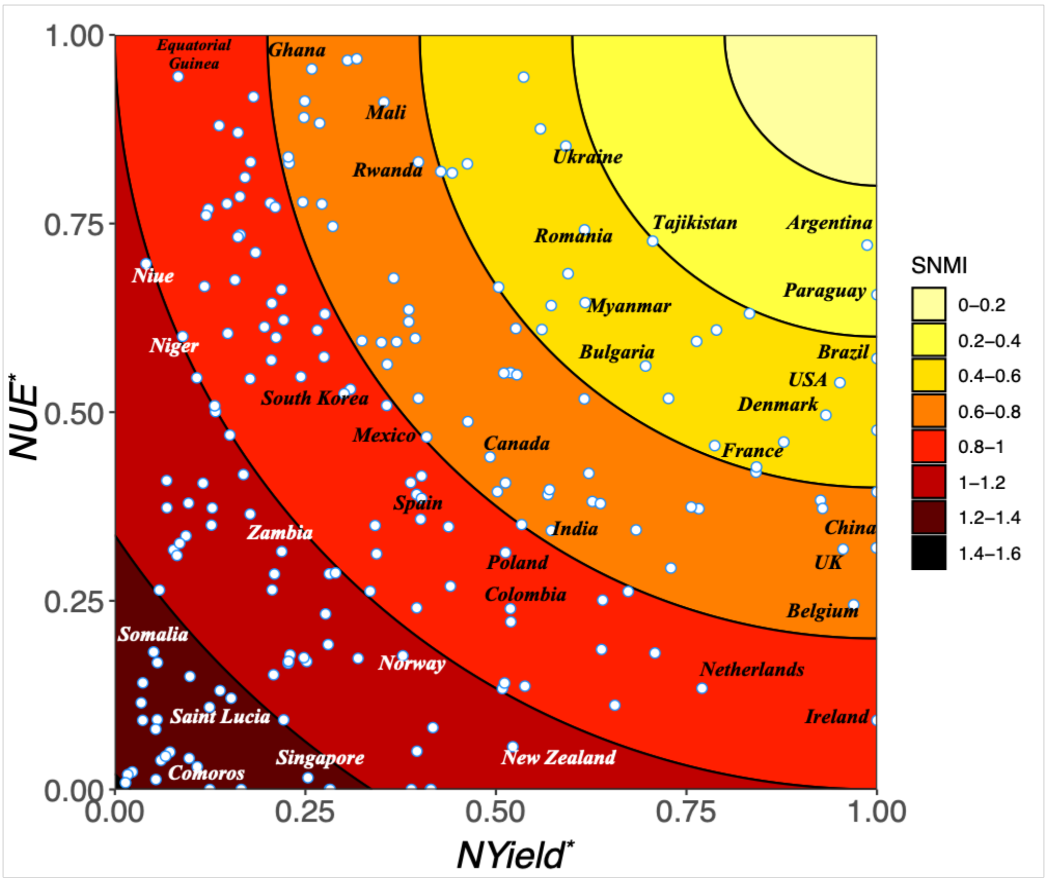

Figure 3. Sustainable Nitrogen Management Index (SNMI) for countries around the world, 2014-2018 (46). NUE represents an indexed NUE_{PB}, and NYield* an indexed R for nitrogen.*

CONCLUDING THOUGHTS

Tracking and improving the right indicators of nutrient use efficiency to reasonable targets offers multiple benefits.

- Several indicators of nutrient use efficiency are measurable at the farm-level, and can be used to make decisions on the efficacy of crop and nutrient management practices.
- We recommend to use the term NUE by default at the crop production system level to describe the ratio of output to input from a partial nutrient balance (NUE_{PB}).
- To properly assess trade-offs, NUE should always be considered in the context of other important indicators of responsible plant nutrition, most often productivity (crop yield) and soil health.
- Assuming yield and soil health are not compromised, higher NUE relates to:
  - Improved economic return to crop nutrient use.
  - Decreased nutrient loss, reducing waste and harm to the environment.
  - Reduced demand for depletion of finite natural resources, and the environmental impacts of producing and transporting nutrient inputs.

For these reasons, we recommend specific formulations of NUE in the context of other relevant indicators to assess responsible plant nutrition in crop production systems. System boundaries, inputs, outputs, and specific calculation need to be specified clearly and comparisons with other calculated values need to be made with care. While NUE_{PB} serves as the most generally relevant formulation of NUE, other specific NUE indicators can be helpful in assessing the attainment of specific aims including profitability of crop production, increased use of nutrient sources derived from recycling, improved soil health, enhanced human nutrition, and reduced nutrient losses related to greenhouse gases, pollution, and biodiversity.

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