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Defining a safe operating space for crop nutrient use

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Many agricultural sustainability programs aim to increase nutrient use efficiency, but also seek to improve productivity per unit of land area, to meet rising global demand without expanding cropland onto natural habitat. Yet, there is no universally agreed approach to balancing these two objectives. Several ideas that place nutrient use efficiency quantitatively in the context of productivity have been published in recent years. Some suggest a safe operating space defined by targets for minimum and maximum nitrogen use efficiency, bounded also by a minimum nitrogen yield and a maximum N surplus. Others use formulas to derive a single mathematical index for sustainable nitrogen management. This presentation will explore the use of such frameworks and their applicability to other nutrients as well as nitrogen, discuss their strengths and limitations, and propose new ideas for their improvement.

Defining a safe operating space for crop nutrient use

The forms and uses of nutrient use efficiency in

1. Responsible plant nutrition
2. 4R Nutrient Stewardship
3. A safe operating space within the planetary boundary for nitrogen

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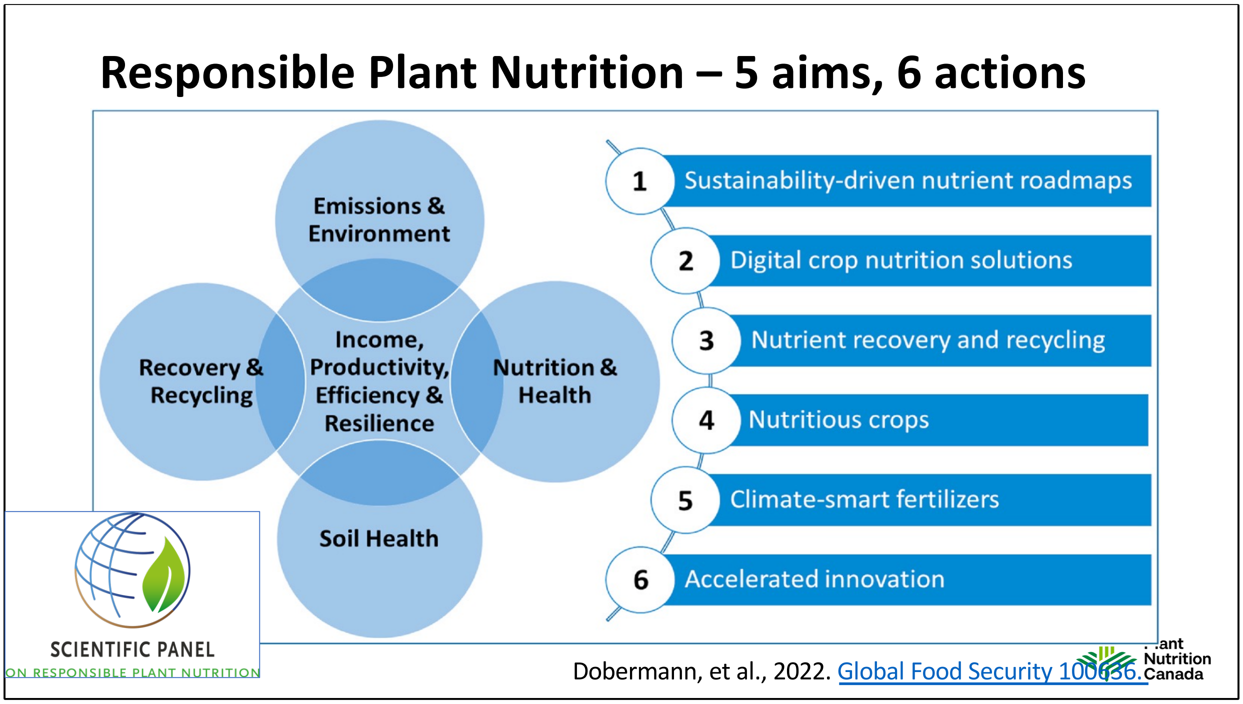


About four years ago, the International Fertilizer Association established an independent Scientific Panel to define and support Responsible Plant Nutrition.

Responsible plant nutrition invokes a new paradigm that adds four new aims to the traditional one of supporting the income, productivity, efficiency and resilience of plant production.

The new aims include a focus on human health through nutrition, soil health in its physical, chemical, and biological aspects, increasing recovery and recycling of nutrients in the economic value chain, and reducing emissions and impact on the environment.

- connected to actions for various players in various sectors, including fertilizer and agriculture but also going well beyond to the whole of the agri-food industry.
- published in Global Food Security journal

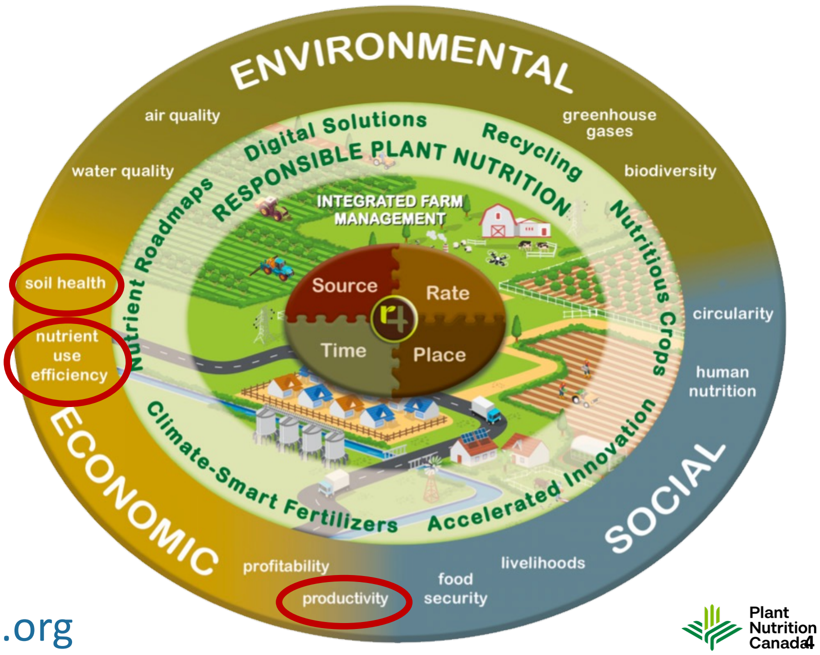
We'll come back to the five aims when we look at specific measures of nutrient use efficiency appropriate to each.

4R in RPN

Twelve performance outcome areas, including NUE.

Farm-level MRV for all 12 not feasible.

What's the minimum # of indicators to focus on at the farm level?



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The Scientific Panel has also considered where the 4Rs fit in Responsible Plant Nutrition.
The source, rate, timing and placement of applied nutrients fits right in the center, as described in the third Issue Brief released by the panel last year.
But RPN, and the success of 4R, also depends on solid agronomy, integrated farm management, and more.
Since the beginning of industry efforts to implement 4R, we have recognized that it connects to many important outcomes.
Among the many shown in the outer circle, there is recent global emphasis on food security, greenhouse gas emissions, and biodiversity.
Making progress on these demands improvements in others including productivity, profitability, nutrient use efficiency, and soil health.
Without forgetting the quality of water and air, human nutrition, livelihoods, and circularity.
Measuring, reporting and verifying the impact on all these performance areas is not feasible.
This raises the question of what is the minimum indicator dataset needed?
The focus often turns to nutrient use efficiency.
But my aim today is to show that it can't be isolated; it needs to be considered in the context of productivity and soil health.

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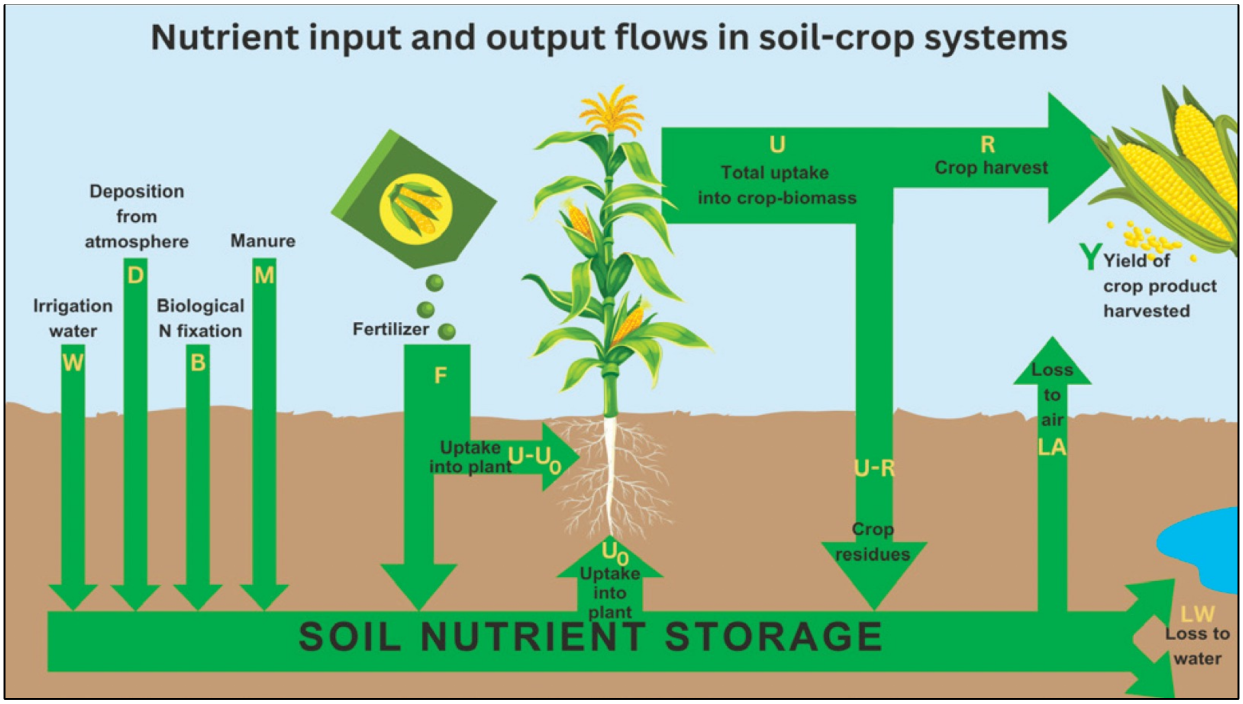
DEFINING NUTRIENT USE EFFICIENCY IN RESPONSIBLE PLANT NUTRITION

Issue Brief 04, August 2023

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.

The Science Panel's most recent Issue Brief gives insight into defining nutrient use efficiency, and identifying different forms useful for the different aims of responsible plant nutrition.



Many forms of nutrient use efficiency can be defined, depending on the aspects of the soil-crop system being considered.
Generally, it's a ratio of the outputs on the right, to the inputs on the left.
But it's always important to look at what is included and excluded.
The output is most often yield, Y, or crop removal of the nutrient, R.
Losses to the air or water, or increases or decrease in soil nutrient storage, are important to the total balance, but not usually are represented as the inefficiency, or one minus efficiency.
Inputs may include fertilizers, manures, biological fixation for nitrogen, deposition from the atmosphere, and nutrients in irrigation – and sometimes in seeds and other inputs as well.
When focusing on fertilizer, the uptake without fertilizer, U sub 0, can be considered to represent everything else plus what the soil supplies, and the difference between uptake and U sub 0 is called fertilizer recovery.

NUE indicators

Fertilizer		Crop	
PFP – partial factor productivity	Y/F	**IE** – internal efficiency	Y/U
AE – agronomic efficiency	$(Y-Y_0)/F$	**PE** – physiological efficiency	$(Y-Y_0)/(U-U_0)$
RE – recovery efficiency	$(U-U_0)/F$	**NHI** – nutrient harvest index	R/U
		NC – nutrient concentration	R/Y

System	
NUE-PB* – partial nutrient balance	R/(F+M+B+D)
NUE-FG – farm gate nutrient balance	EXPORTS/IMPORTS

**** NUE-PB is the most universal***

The Issue Brief lists some of the more commonly used forms of NUE in three groups, fertilizer, crop and system indicators.
The one that is simplest for a farmer to track is partial factor productivity, yield per unit of nutrient applied.
To more accurately reflect the outcome of applying fertilizer, agronomic efficiency or recovery efficiency can tracked but require a lot more resources.

Efficiencies within the crop can also be important.
These include internal and physiological efficiency, the relation of yield to nutrients taken up.
They can also include less traditional ratios, like nutrient harvest index and nutrient concentration.

The indicator most relevant to environmental impacts and responsible use is a partial nutrient balance, the ratio of nutrient removal to the inputs to the cropping system.
It can also be calculated as a farm gate balance.

NUE indicators for the Five Aims of RPN	
1. Income, **productivity**, efficiency & resilience of farmers	**a) PFP & NUE-PB** (on-farm adaptive assessment) b) AE, RE, IE, PE (agronomic & genetic research)
2. Increase nutrient recovery & **recycling** from waste	**a) NUE-FG** (opportunity to improve on-farm) b) AE, RE (efficacy of recycled products)
3. Lift & sustain **soil health**, including soil carbon	**a) NUE-PB** (potential for surplus or depletion) b) NHI (nutrients in crop residues)
4. Enhance **human health** through nutrition-sensitive agriculture	**a) NC** (nutrients in foods & feeds) b) NHI (nutrient transfer to harvested product)
5. Minimize GHG **emissions**, nutrient pollution, & biodiversity loss	**a) NUE-PB** (potential for nutrient losses) b) RE (potential losses due to inefficient fertilizer use)

Specific measures for specific aims for specific contributors

In this table we look at the five aims again, and consider which indicators are most relevant to their achievement, and useful to which users.
Partial factor productivity and partial nutrient balance fit best for improving productivity and profit.
They can be part of on-farm adaptive assessment, since they can be measured or estimated from production data.
The more sophisticated indicators of agronomic, recovery, internal and physiological efficiencies are useful to scientists and crop breeders for understanding the specific contributions of applied nutrients to yield.
In the area of nutrient recovery and recycling, a farm-gate balance can identify farms that may not be utilizing all the nutrient resources they have on-farm. For those involved in making products from nutrients extracted from wastes, measuring the agronomy and recovery efficiencies from these products determines the availability.
For maintaining soil health, a partial balance can indicate whether nutrients are accumulating or being depleted. Additionally, nutrient harvest index may be useful to know, particularly to assess carbon to nitrogen ratios of crop residues.
When it comes to human health, nutrient concentrations may be important. There may be trade-offs with other NUE indicators, for example, partial factor productivity could increase at the expense of nutrient concentrations.
In terms of minimizing losses, again a partial balance is the most relevant. While it can't be assumed that anything less than 100 % is lost to the environment, the fraction below 100 can represent potential losses.
Summing up, it seems that partial balance is the most frequently useful, but does not apply to all aims. Neither does any of these NUE indicators fully address any of these aims, notwithstanding their considerable contribution.

NUE – the silver bullet?

- Even with appropriate NUE indicators for each of the five aims, a gap remains in on-farm assessment of sustainable plant nutrition practices.
- Maximizing NUE involves trade-offs with productivity and soil health
- Optimizing NUE requires accounting for productivity and soil fertility

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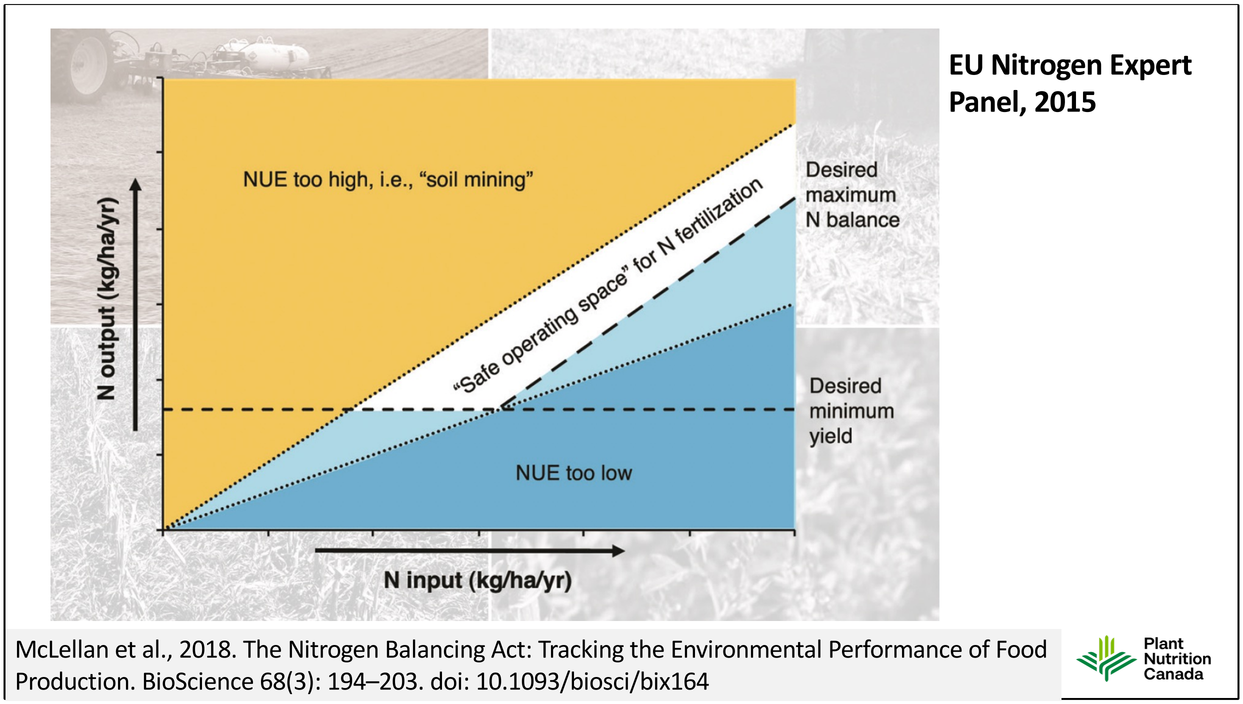
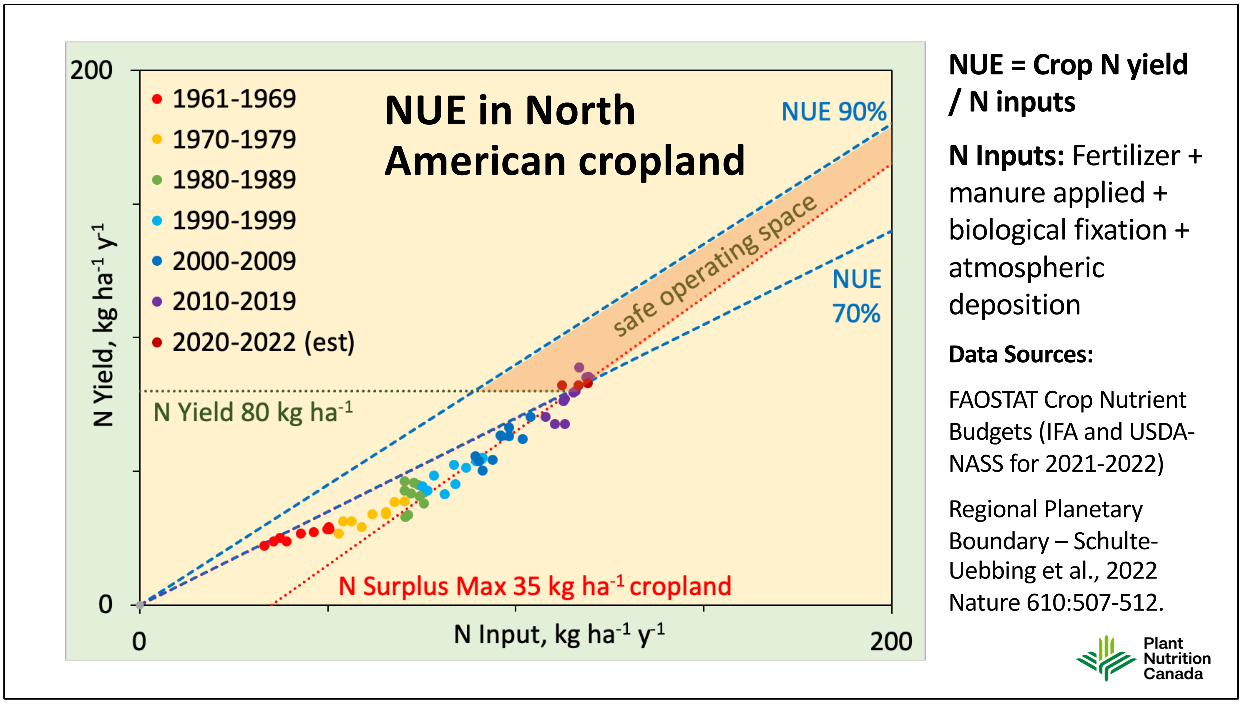


A safe operating space concept developed around ten years ago involves plotting nutrient output against nutrient input.
It ensures that productivity continues to be considered, in the form of nutrient output.
It allows for the setting of a minimum productivity, and also a maximum nutrient balance or surplus.
This makes a mot of sense for crops whose mineral nutrient content is valued, such as in the form of protein, or nutritional minerals.
But it makes less sense for crops like sugar cane or sugar beets, produced mainly for carbohydrates, or for oilseeds, spices, vegetables and fruits.
It allows for setting of regional targets for an optimu range of nutrient use efficiency, and defines a space where "soil mining" is likely to be occurring.
Unfortunately it makes NUE a little more complex – the NUE represented by any point in this space is the slope of the line to the origin. That's simple for scientists, not necessarily for policymakers.

Figure 3. An illustration of the safe operating space concept (inner diagram) in the broad context of nutrient management (outer diagram). The inner diagram (modified from EU-NEP 2015) shows the relationship between total nitrogen (N) input (from fertilizer, manure, and biological N fixation), N outputs (N removed in harvested grain), N use efficiency (NUE), and N balance. A safe operating space requires that NUE is sustained within an accepted range; values that are too low (blue shaded area) are inadequate to meet food production goals and are inefficient for resource use, whereas values that are too high (gold shaded area) risk mining soil organic matter. Likewise, we assume that there is some minimum productivity (yield) goal, shown here by the horizontal dashed line, and some acceptable maximum level of N balance, shown here by the diagonal dashed line. Expert judgment is needed to define appropriate values of N balance, NUE, and yield for a given cropping system and ecoregion. The intersection of these criteria (the white space in the inner diagram) represents the safe operating space for that cropping system and ecoregion. The outer diagram shows the broad suite of approaches to nutrient management (from top left: improved fertilizer management; substitution of manure for synthetic fertilizer; use of legumes as an alternative nitrogen source; use of cover crops to tighten internal nutrient cycling), which can help move a cropping system into the safe operating space.



Here we have applied the concept to Nitrogen in North American cropland.
The partial balance considers nitrogen in harvested crops as output, and inputs include fertilizer, manure, fixation and deposition.
Data are from the recent FAO Crop Nutrient Budgets up to 2020, with some exptrapolations based on more recent data from IFA and USDA-NASS.
N yield has been increasing through the time period, from 1961 to 2022.
Here I use 80 kg N per hectare as a minimum for the safe operating space. Diminishing yields from where they are doesn't help sustainably support increasing demand.
Only in the past two or three decades have yields increased faster than inputs, crossing the 70% line.
We might think 70% is impressive, but keep in mind that aggregate efficiency hides areas of low efficiency by averaging across areas of high efficiency: soybeans – assumptions lead to an efficiency of about 99%, and land with a negative N balance.
The maximum N surplus here, 35 kg per hectare, is defined by a regional planetary boundary published in the 2022, applied to cropland. Note that the boundary for surplus depends on many assumptions, and you could define a much wider range of around the 35, looking more closely at this and other sources that could be cited.
We can debate as to how well this concept scales – can a field of corn be compared with a field of soybean in this way? And how about much different crops like almonds, cotton, rice, and sugarbeets? Likely crop and region specific targets for these three parameters would need to be agreed on.
Note that as we continue to increase both yields and NUE, the safe operating space becomes narrower
Figure 2. Progress towards reaching a safe operating space for nitrogen use on North American cropland, 1961 to 2020. The desirable window of N use efficiency (calculated as NUEPB) is shown by the dashed blue lines (70-90%). The dotted red line depicts a maximum acceptable N surplus of 35 kg per ha, calculated by dividing the planetary boundary for surplus N by the area of cropland. The dotted horizontal line (green) represents a current crop productivity level of 80 kg N per ha per year, which would rise further as food demand increases in the future. Data from the global cropland N balance.

FAO. 2020. FAOSTAT Soil Nutrient Budget database. FAOSTAT. http://www.fao.org/faostat/en/#data/ESB.
Schulte-Uebbing, L.F., A.H.W. Beusen, A.F. Bouwman, and W. de Vries. 2022. From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610(7932): 507–512. doi: 10.1038/s41586-022-05158-2.

Safe Operating Space – strengths & limitations

STRENGTHS

- Shows productivity in relation to nutrient input
- Shows an optimum range for NUE
- Shows a limit for surplus N
- Scalable from field to global
- Allows for targets specific to cropping systems and eco-regions

LIMITATIONS

- Depiction of NUE as slope can be confusing
- Equating productivity with N removal not relevant to all crops
- No explicit depiction of impact on soil fertility or soil health
- Does not reduce to a single number

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Sustainable Nitrogen Management Index

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

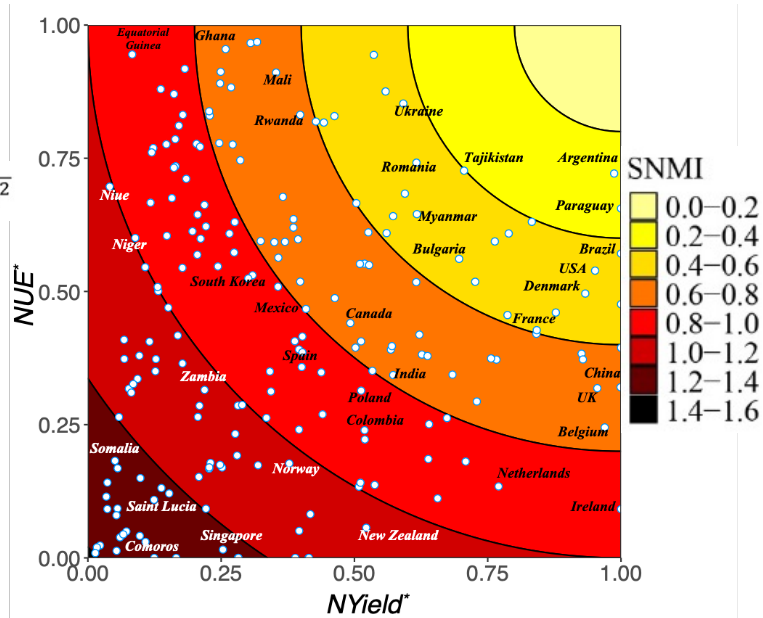
R^* = indexed crop removal of nutrient

= Nyield*

NUE = outputs/inputs

(adjusted if >1)

Ranges from 0 to $\sqrt{2}$ with low values desirable



X. Zhang et al., Sustainable Nitrogen Management Index: definition, global assessment and potential improvements. Front. Agr. Sci. Eng. 9, 356–365 (2022), doi:10.15302/J-FASE-2022458

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

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 (Wolf et al., 2022), and in the SDGs Index and Dashboard (Sachs et al., 2022).

X. Zhang et al., Sustainable Nitrogen Management Index: definition, global assessment and potential improvements. Front. Agr. Sci. Eng. 9, 356–365 (2022), doi:10.15302/J-FASE-2022458.

M. J. Wolf, J. W. Emerson, D. C. Esty, A. Sherbinin, Z. A. Wendling, Environmental Performance Index: ranking country performance on sustainability issues (Yale Center for Environmental Law & Policy, New Haven, CT, 2022).

J. D. Sachs, C. Kroll, G. Lafortune, G. Fuller, F. Woelm, Sustainable development report 2022 (Cambridge University Press, 2022).

SNMI – strengths & limitations

STRENGTHS

- A single number
- Captures progress toward increasing benefits and decreasing losses
- Reference NUE may be <1
- Reference yield could use any measure relative to site-specific potential

LIMITATIONS

- Same score for different regions (e.g., Ghana=Canada=China)
- Requires disaggregation

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The 4R advantage: MRV demands documented practices to model outcomes

Specific practices to increase NUE

- Right source, rate, time & place
  - EEF
  - Predict optimum rate
  - Just-in-time to match demand
  - Place in root zone
- Crop yield improvement
  - Increase crop nutrient demand
  - Genetic and agronomic

Specific practices to reduce losses:

- N_2O emissions
  - Improve NUE
  - Inhibitors and controlled-release
- Loss of phosphorus
  - Increase NUE where it is low and where soil test P is high
  - Keep soluble forms of P out of runoff paths – placement & timing

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Including 4R principles and practices in emission reduction programs and protocols offers opportunity to capture greater reductions in emissions, and makes monitoring, reporting and verification (MRV) possible. A program based on 4R builds on the strengths of a nitrogen surplus – nitrogen use efficiency approach, and addresses most of its limitations. Choices of the right sources, timings, and placements have effects on emissions beyond those accounted for in NUE improvement and reductions in nitrogen surplus. Accountability principles for 4R programs encourage the reporting to trusted third parties of tracked data on the specific combinations of source, rate, time and place for each nutrient application, along with the outcome measure of a crop nutrient balance. These data are essential to document progress in both reducing emissions from fertilizer and improving the carbon footprint of crop production.

MRV requires data on 4R practices, as well as NUE and yield, to assess contributions to all five aims of responsible plant nutrition

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- Comprehensive assessment of sustainable crop production requires additional indicators.

The NUE indicators for fertilizer, crops, and system all contribute to assessment of sustainable farming.
Specific contributors can use specific indicators to assess progress toward the five aims of responsible plant nutrition.
Comprehensive assessment of sustainability needs indicators beyond NUE.
Monitoring, reporting, and verification (MRV) in sustainability programs will require data on 4R practices as well as the outcomes discussed here, to assess contributions to all five aims of responsible plant nutrition.