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Position Paper
Nitrogen Use Efficiency and Nutrient Performance Indicators

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About the Global Partnership on Nutrient Management

The Global Partnership on Nutrient Management (GPNM) is a multi-stakeholder partnership comprising of governments, private sector, scientific community, civil society organizations and UN agencies committed to promote effective nutrient management to achieve the twin goals of food security through increased productivity and conservation of natural resources and the environment. The United Nations Environment Programme (UNEP), through the Coordination of Office of the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), provides the Secretariat of GPNM.

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Foreword

This paper offers the technical basis and supporting research for using Nitrogen Use Efficiency (NUE) as a performance indicator to improve global food production and control the potential harmful environmental impacts of excess nitrogen-based compounds from manufactured and animal waste fertilizers. NUE implies a more precise application of nutrients that is based on current agronomic principles in combination with other factors like soil health, water availability, climate, and type of crop.

Since the NUE indicator can be quantified, countries now have an opportunity to evaluate the effectiveness of their own nutrient policies and, at the same time, farmers have the ability to assess the efficiency of their farming practices and nutrient use to increase production and reduce environmental damage. The GPNM recommends NUE as a performance indicator to address nutrient losses within developing and existing global agreements that focus on sustainable development, oceans, climate change, biodiversity, water quality, air quality and soil health.

Greg Crosby
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Nitrogen use efficiency and nutrient performance indicators. GPNM Task Team Report and Recommendations[1]

Rob Norton, Eric Davidson, and Terry Roberts

Summary

The Task Team recommends using Nitrogen Use Efficiency (NUE) to describe partial nutrient balance (also referred to as removal/use or output/input ratio) and note that it can be configured in different ways to show the current starting point (benchmark) from which future improvements can be assessed (progress indicator). NUE can be expressed at different scales from the farm to the country level. Neither a high nor a low NUE is an implicit target, but raising low values, which usually indicate inefficient use of added nitrogen, and lowering very high values, which usually indicates mining of soil nitrogen, will require appropriate interventions at the farm level, so that the farmer engagement is important in achieving progress. The task team recognizes that NUE relates to production and soil health, so it needs to be put in context to other indicators. We also note that significant lags between improvements in NUE and reductions in N pollution of groundwater and surface waters may occur, but nevertheless, increases in NUE and reductions of surplus N in agriculture should eventually lead to lower N pollution.

PREAMBLE

The efficient and effective use of nutrients underpins food security and reduces losses of nutrients to the environment. While balanced nutrition is important, nitrogen in particular is fundamental to raising crops and animals to feed the world now and in the future. Much of the increase in food production over the past half century can be attributed to the use of synthetic nitrogen fertilizers. However, when used at the wrong time, or the wrong rate, or in the wrong form and put in the wrong place, adverse impacts can occur as nitrogen flows through the environment.

The importance of reconciling nutrient removal with nutrient additions has been recognized through the United Nations Environmental Program's view that there is a need to define and then assess trends in nutrient performance. The Sustainable Development Solutions Network has also proposed that crop nitrogen use efficiency should be an indicator of progress towards a goal to end hunger, achieve food security, improve nutrition, reduce pollution, and promote sustainable agriculture. Science and industry have supported the development of appropriate indicators to represent the balance between underuse of nitrogen that can lead to low production and the depletion of soil fertility, with excess nitrogen that can lead to adverse environmental impacts. Using nitrogen use efficiency estimation is consistent with the indicators proposed by other agencies and the fertilizer industry.

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[1] Revised April 8, 2015

The focus of this report is nitrogen and similar principles could be applied to estimating phosphorus, potassium or sulfur nutrient use efficiencies.

DEFINING NITROGEN USE EFFICIENCY

Nitrogen use efficiency (NUE) can be defined in many ways depending on the purpose to which the indicator will be put. Agronomic efficiency or apparent recovery efficiency are appropriate performance indicators, especially in the selection of more efficient genotypes for nutrient uptake or to assess nutrient transfers among soil pools, but both of these measures require a nil fertilizer application treatment to estimate the extra yield due to the added fertilizer. Such measures are normally only available on research plots limiting their usefulness in non-research settings. We recommend using partial nutrient balance to measure NUE. Also called the removal/use ratio or the output/input ratio, this indicator is derived from the sum of N in all of the products removed from the field (i.e., the harvested crop or livestock product and any stover or other material removed) and the sum of all inputs of N to the field, farm or region (i.e., fertilizer, imported animal manure, compost, green manure or other soil amendments, imported animal feed, and biological N fixation; note that atmospheric N deposition is usually ignored because it is usually small relative to agricultural inputs, but it could be included where deemed important). As such, NUE reflects the proportion of nutrient recovered in produce, within the boundary of the system described, relative to the amount of N entering the site:

NUE = sum-of-outputs/sum-of-inputs

NUE does not describe pathways of internal N transformation within a system (e.g., N mineralization or nitrification), nor is it necessarily a direct quantitative estimate of N loss from the system, because N not removed in the harvest might remain on site in the soil. Over the long term, however, changes in soil N stocks are usually low relative to inputs and outputs, and therefore, low NUE values over multiple years are reasonably reliable indirect indicators of probable significant N loss to the environment.

An important advantage of this definition of NUE is that the data are generally available at both the farm level and the national accounting level. On the farm, fertilizer (and imported manure) amounts are usually known, as is the harvest volume or mass (e.g. bushels/acre or tonnes/hectare). The concentrations of N for manure and harvest products are often not known for specific farms, but they can be estimated from regional literature values. At the national and sub-national level, data on production by commodity type (e.g., maize, wheat, rice, other crops, dairy products, and meat) are estimated by governments and the FAO when real data are not available. The FAO also gives data on the total apparent fertilizer consumption by country, but these data are not disaggregated by crop or region. Attempts have been made in the scientific community to disaggregate national data to crop specific application rates on agricultural areas (e.g. Potter et al., 2011), that could be used as baselines or reference values. IFA has released two reports on fertilizer use by crop by country from collected data (Heffer 2009, 2013), but these do not cover all countries.

Although there are some data limitations and uncertainties, both inputs and outputs can be estimated locally and nationally, and from those estimates, NUE can be derived.

A disadvantage of NUE is that it, alone, is often inadequate for assessing agricultural sustainability, so that NUE data must be interpreted in the context of other data. Different crop types are likely to have different NUE, and national and regional NUE values may reflect the particular mix of farming systems within those areas. Maize generally has lower NUE than wheat, and so a country or farmer growing a lot of wheat may report relatively high NUE, not necessarily because of particularly efficient nutrient management practices, but because of the type of crop that the soils and climate best support. Table 1 gives examples of annual NUE for different crops from selected countries.

Table 1. An example of NUE by country and crop. Data were derived from FAOSTAT (Crop production and area sown), IFA (Fertilizer use by crop) and IPNI (Crop product nutrient concentrations). Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Wheat	Maize	Rice	Other Cereals	All Cereals	Soybean*	Palm	Other Oilseeds	Sugar
Argentina	1.28	0.99	2.26	1.67	1.21	1.20	-	3.23	2.17
Australia	1.10	1.06	2.60	0.86	1.02	-	-	0.63	0.93
Bangladesh	1.27	1.06	0.56	-	0.57	-	-	1.01	0.89
Brazil	0.99	0.85	0.97	0.87	0.88	1.20	0.55	1.02	1.83
Canada	0.86	0.70	-	1.05	0.89	1.18	-	0.94	-
Chile	0.63	0.51	0.83	0.81	0.63	-	-	1.08	-
China	0.54	0.40	0.47	0.66	0.47	0.80	0.32	0.41	0.38
Egypt	0.59	0.26	0.53	0.64	0.45	0.74	-	0.19	0.44
EU-27	0.96	0.53	0.86	1.09	0.90	1.13	-	0.95	-
India	0.46	0.36	0.40	0.50	0.43	0.90	-	0.49	0.64
Indonesia	-	0.43	0.65	-	0.59	0.94	0.86	0.00	1.07
Iran	0.78	0.46	0.48	0.79	0.71	1.05	-	0.43	0.26
Malaysia	-	0.38	0.37	-	0.37	-	0.69	11.68	1.07
Mexico	1.22	0.39	0.60	5.12	0.62	-	0.08	0.94	1.29
Morocco	1.78	0.53	0.55	1.30	1.52	-	-	0.33	0.13
Pakistan	0.40	0.30	0.34	0.53	0.38	-	-	1.26	0.39
Philippines	-	0.75	0.97	-	0.90	-	0.46	0.05	2.08
Russia	1.63	0.46	0.71	2.79	1.78	1.08	-	4.87	-
South Africa	1.46	0.54	-	1.70	0.66	1.20	-	1.25	0.79
Thailand	-	0.64	0.94	0.88	0.90	1.12	0.71	0.26	1.20
Turkey	0.73	0.46	0.84	1.30	0.81	0.93	-	0.55	-
USA	0.73	0.61	0.55	0.77	0.64	1.22	-	0.60	0.43
Vietnam	-	0.36	0.65	-	0.60	0.74	-	0.05	0.62
World	0.77	0.55	0.56	1.26	0.68	1.15	0.81	0.73	0.89

* Soybean N balance was estimated as the N removed divided by the sum of N applied plus fixed N. The amount of fixed N was estimated as 0.8 of the N removed.

A second complication of NUE estimates is the consideration of crop rotations. Where maize and soybeans are rotated on the same field annually, for example, NUE would have to be calculated for a two-year rotation cycle in order to account for the N inputs from soybeans in one year that could remain as inputs to the maize crop the follow year. Where longer and more complex crop rotations are employed NUE estimates would need to consider the whole crop cycle and not just crops in isolation.

Biological N fixation (BNF) by soybeans, pulses, and other leguminous crops presents a third complication. Assumptions must be made regarding the fraction of N within the plants that is from BNF and the fraction of total plant N that is removed. An estimate of total plant N times the fraction from BNF must be included in the input term to calculate NUE. Such estimates are available in the agronomic literature (e.g. Salvagotti et al., 2008; Peoples et al., 2009) and can be provided in simple look-up tables for use by farmers or by national agronomic policy analysts, similar to look-up terms now in use for calculating greenhouse gas emissions for IPCC accounting requirements.

A fourth potential complication involves the more complex accounting that is needed to estimate NUE in mixed crop-livestock operations. Outputs could include some crop products if they are exported and not used entirely within the farm for feed, as well as the dairy or animal products, including any manure that might be exported to another farm rather than being used internally. Inputs would include fertilizers and feed supplements. Again, these are not insurmountable problems, but do add a layer of complexity to the needed accounting.

A fifth issue is that NUE is best interpreted in terms of a trend of changing NUE over time, rather than attempting to interpret a single snapshot of a single year's estimate for a farm or a nation. As mentioned above, a single estimate of NUE is strongly influenced by the crop or animal production system, and it is difficult to define whether a single estimated value of NUE is inherently good or bad. If repeated over time, however, a trajectory of NUE values can provide a very useful indicator of whether progress is being made to improve NUE within a given cropping system within the context of the climate, soils, and commerce of the region.

Despite these challenges, the inclusion of all the input and output components in estimating NUE is essential to assess if there is sufficient nutrient supply for high yields and to maintain or even improve soil health. Using animal manure, recycling plant material (e.g. composts, processing waste streams) and integrating legumes into cropping systems are all important strategies to increase soil organic matter and improve soil structure, leading to synergies between organic and mineral fertilizers and improving NUE.

DERIVING NUE

We envision an accounting system similar to the IPCC system for calculating greenhouse gas emissions, but designed to facilitate estimating NUE at a variety of scales, from the farm to the nation. Where site-specific data are not available on N concentrations of crops and manures and for BNF contributions, simple lookup tables could be provided. For example, a farmer who has produced X tonnes per hectare of maize could look up the N concentration of grain in that region (Y %N) and estimate the output term as:

Output N = X * Y/100.

If the harvested products were analyzed for N concentration, that value could be used in lieu of those from lookup tables.

Most commercial fertilizers come with an estimate of N concentration, so the input is simply the application rate in kilograms of product per hectare multiplied by the concentration of N in the product. Nutrient concentrations of manures, however, are more variable. If concentration data are available for a specific manure source, they could be used, but when specific concentration data are not available, a regionally pertinent lookup table (e.g. showing the average N concentration of chicken manure in the mid-Atlantic states of the USA) could be provided to the farmer.

Inputs of BNF by leguminous crops would require regionally appropriate estimates of the total amount of N in the crop (crop mass multiplied by the N concentration of the mass), multiplied by the fraction of N provided by BNF (usually 60-80%, e.g. Peoples et al., 2009). Not all the BNF remains in the field, so the proportion of the N removed from the site in grain or other crop products (harvest fraction) needs to be considered.

BNF inputs =
crop mass produced X %N of the crop mass X BNF fraction X (1-harvest fraction)

Data for fertilizer use can be derived from existing sources, such as sub-national agricultural extension and research stations for farm-level operations. For national accounting, data are currently available from IPNI for average nutrient concentrations (IPNI 2012), FAO for production (FAOSTAT 2014), and IFA for fertilizer use (IFA, 2015; Heffer 2009, 2013).

Input N = Applied manure N + BNF + Applied fertilizer N

NUE can be derived at a range of scales, but downscaling from national to regional data will require additional qualification of the input and output. It is also appropriate to investigate upscaling of farm level nutrient balances to validate downscaled national data.

INTERPRETING NUE ESTIMATES

When NUE = 1, the amount of nutrient removed equals the input of N. When NUE < 1, more N is being applied than is being removed, and the N not removed could either be stored in the soil and/or flow through to the environment causing ecosystem degradation. When

NUE > 1, more N is being removed than is being supplied, which indicates that the soil is being mined of nutrients, eventually depleting soil fertility.

While NUE is the ratio of outputs/inputs, "N surplus" is defined as the difference (inputs-outputs). When NUE <1, the surplus is positive, indicating the likelihood of loss of N to the environment.

No biological systems, including crop and animal production systems, can be 100% efficient, so a goal of NUE = 1 and a surplus of zero is unrealistic. Nor do we know how efficient (how close to an NUE of 1) cropping systems could become and still maintain productivity. It is desirable however to approach NUE =1 for long term system sustainability. In general, animal production systems are less efficient than cropping systems because animals inherently produce N-rich wastes in urine and feces, which are challenging to recycle with high efficiency. While it is very difficult to establish hard and fast NUE goals, we can generalize that when NUE < 0.5, there is probably a large opportunity for improving NUE. At the other extreme, when NUE > 0.9, it is likely that efficiency cannot be improved further without risking mining of soil nutrients.

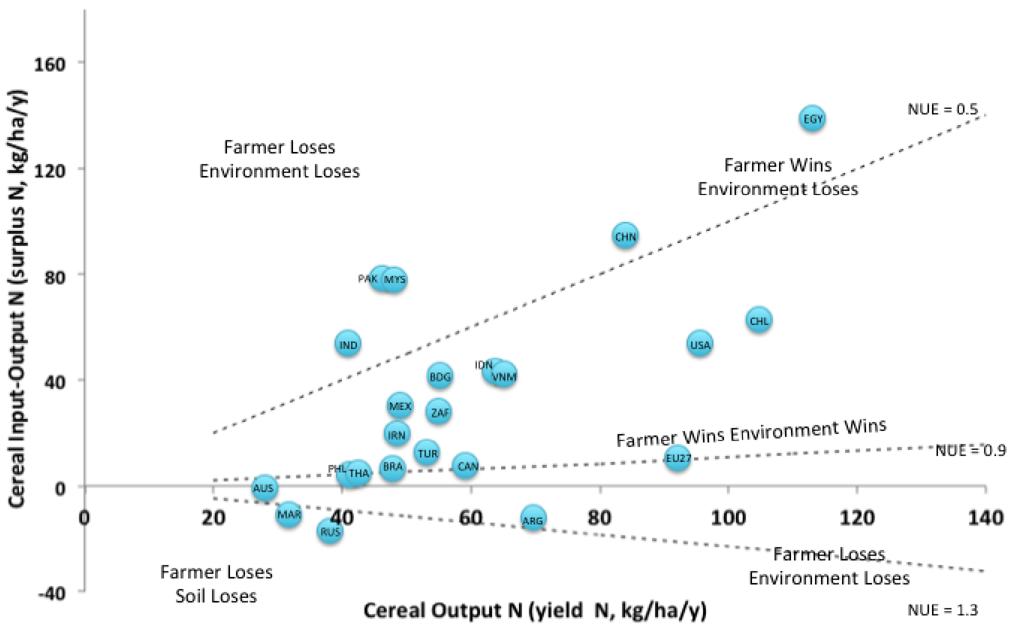

Figure 1: NUE for cereals, graphed as the surplus of N (inputs minus outputs) versus removal (output) of N. The dotted lines show values of NUE according to the relation between inputs and outputs. Biological N fixation and manure use are not considered in this example. Each circle represents a country indicated by UN Country 3 letter code.

However, this should not imply that NUE values between 0.5 and 0.9 are necessarily acceptable, because, as already noted, an NUE value of, say 0.7, may be good for some systems in some places and not so good for other systems in other places. For example, many of the countries that fall between the 0.5 and 0.9 NUE lines in Figure 1 are likely to have potential for further improvements, and the differences among countries may reflect differences in the crop grown, the use of manures and the importance of legume based rotations, as much as differences in nutrient management practices. Figure 1 is shown as an example of NUE for cereals only, where Output-N is plotted on the X axis and N surplus (Input-N minus Output-N), on the Y axis, and the dotted lines show values on the X and Y axes that are consistent with a specific NUE value, which is a mathematical outcome of the definitions of N surplus and NUE. Any number of lines could be drawn, but the figure here shows only three – NUE = 0.5, 0.9, or 1.3 – as benchmarks. The data to produce this figure are shown in the Appendix table and are pre-Tier 1 values as they do not contain estimates of BNF or manure inputs, and N contents were averages not regionally specific.

Rather than the snapshot comparison shown in the example in Figure 1, it is best to use an indicator based on a trajectory of NUE values over time to demonstrate if progress on improving NUE is being made or if an upper efficiency limit is being approached. Figure 2 shows a hypothetical example of a farm growing maize in the mid-western region of the USA (Davidson et al. 2015). It could represent a single farm or an average for the region or nation. The square shows a one-time estimate of NUE of 0.67. The arrows show the trajectory that would be consistent with improved NUE over time. Hence, the initial point is a benchmark by which progress can be demonstrated. We believe that this type of figure could be generated easily through an appropriate canned algorithm (such as a pre-formatted Excel spreadsheet or a customized user-friendly software package) that would require only very simple data inputs. As each year's data is entered, the trajectory for the farmer or for the nation could be tracked.

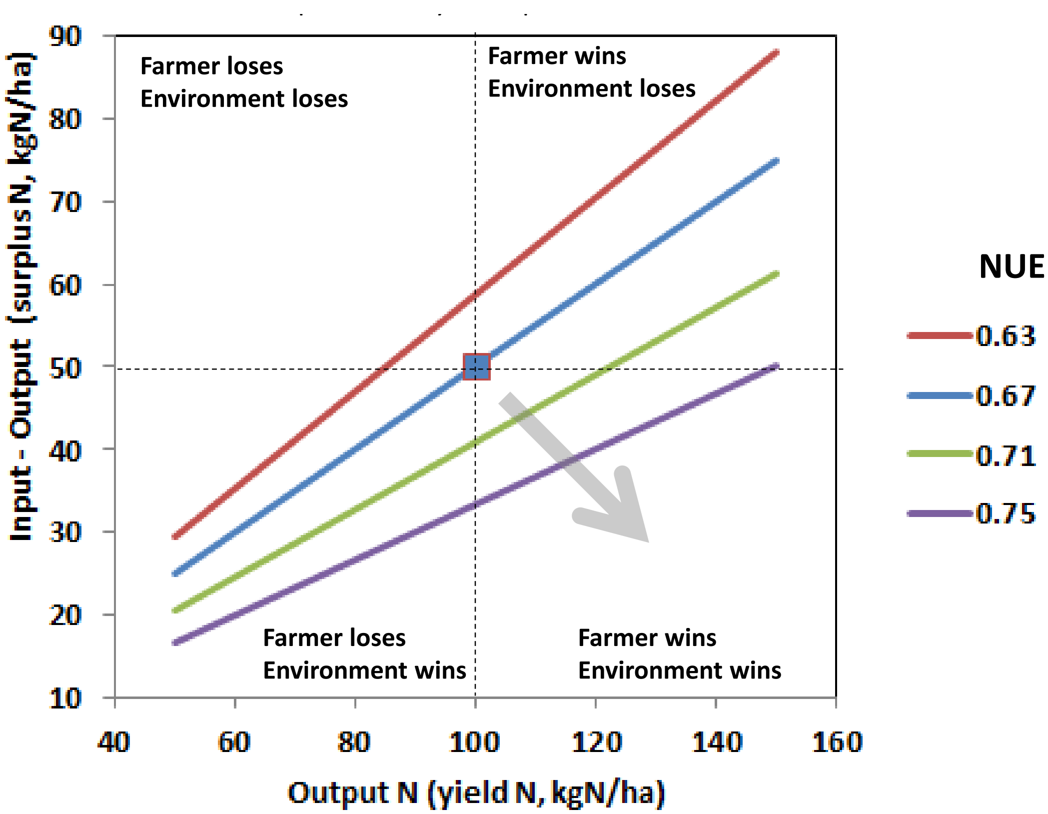

Figure 2. Diagram of how NUE can improve relative to an initial benchmark value and who wins when the trajectory over time is to the right or left, up or down in the plotted

parameter space. A win-win situation for both the farmer and the environment occurs when NUE increases, N surplus decreases, and crop yield (Output N) increases as plotted values on this graph move from the benchmark value to the lower right (after Davidson et al 2015.)

The example in Figure 2 applies to the high yielding regions of the world, where N surpluses are often positive and environmental pollution associated with excess N is a societal concern. In contrast, parts of the developing world face a problem of too little N input to agriculture due to unfavorable crop/fertilizer price ratios or lack of availability of fertilizers or other sources of N inputs. Figure 3 extends the range of surplus N values shown in Figure 2 to negative values on the Y axis, which illustrate mining of soil N, because N removed in harvest exceeds N inputs. In this case, the win-win option for farmers and the environment results from movement toward the upper right of the graph, where crop yields increase, N mining decreases (i.e. NUE declines below 1), and N surplus remains relatively small. However, how far to the upper right is desirable before risking significant and damaging loss of N to the environment is difficult to specify.

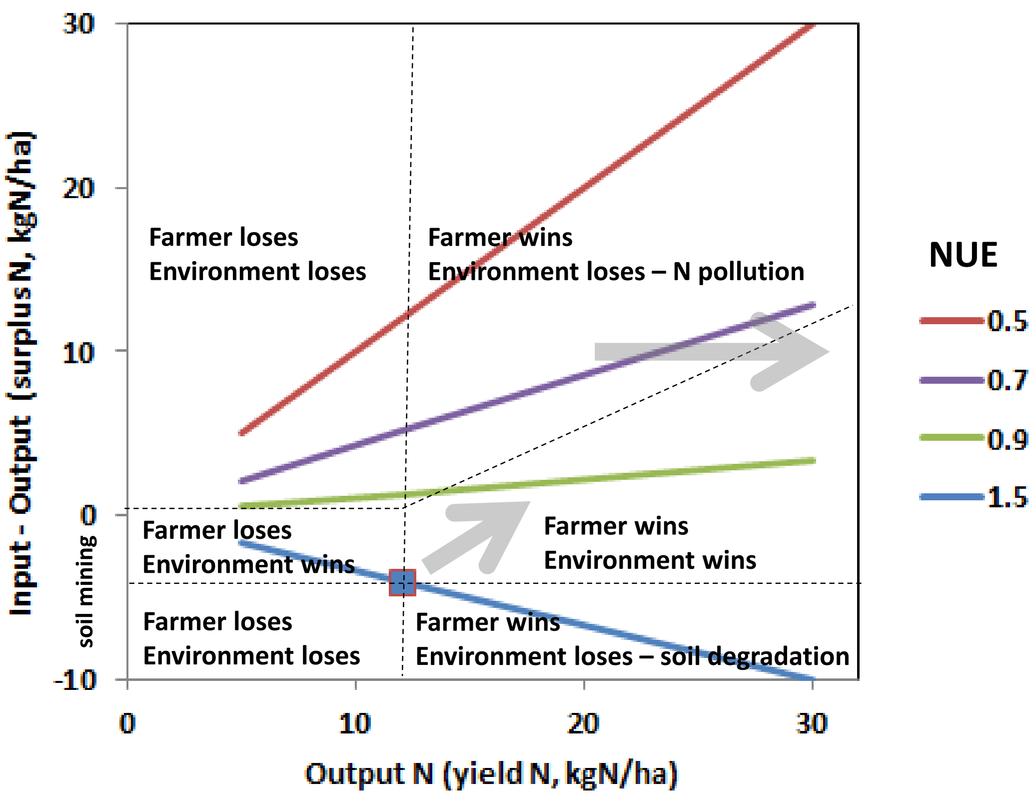

Figure 3. Application of the concepts shown in Figure 2 to a lower yielding or less developed country where mining of soil N is occurring due to NUE >1 and N surplus < 0. While the farmers in high yielding environments should move to the lower right to improve

NUE, farmers in low yielding environments farmer should move toward the upper right, at least initially.

A TIERED APPROACH TO NUE ACCOUNTING

Because the availability and quality of data on N inputs and outputs vary regionally, we envision a tiered system for reporting NUE estimates, patterned after the IPCC system:

Tier I: A system of global default values provided in lookup tables for N concentrations of crop products, fertilizers, manures, other soil amendments, and BNF inputs. Simple mathematical equations would be provided, demonstrating how these default values would be combined with local or national "activity data", which in this case, would be yield data (e.g., bushels/acre, tons/hectare, liters of milk/cow, etc.) and input rates (e.g., fertilizer application rates, manure application rates, daily feed supplement rates, etc.) to derive estimates of farm-level or national-level inputs of N, outputs of N, N surplus (inputs minus outputs), and NUE (outputs/inputs).

Tier II: Where data on N concentrations are available at the site, regional, or national level that can be demonstrated to be more specific to the application area, and hence likely to be more geographically and systems specific, these data may be substituted for the global default values recommended for the Tier I approach. The equations would be the same as in Tier I.

Tier III: It is possible to model agronomic inputs and outputs of N in response to factors such as economic conditions, commerce, soils, climate, crop performance characteristics, and available technology. Where such models have been developed and validated at the farm scale or larger scales, such as by survey or nutrient audits, they could be used to estimate NUE and N surplus. Indeed, models of N input-output have been developed at the global scale (Bouwman et al., 2011).

At present, the publication of FAO production data is about two calendar years behind the present. IFA fertilizer consumption statistics are also released two years after completion of the campaign. The IFA fertilizer-use-by-crop data are available only for three periods, and the degree of temporal variation in product nutrient concentration is not available. It would seem unlikely that with the current procedures that country-level NUE could be reported annually, and within one year of the data period. Aggregated moving means of triennial NUE values may best serve the purpose of a moderate cost for data collection balanced with a reliable estimate. Furthermore, year-on-year changes are likely to be minimal so that triennial monitoring may be sufficient.

NUE AS A NUTRIENT PERFORMANCE INDICATOR

The purposes for the application of these performance metrics are as indicators of the outcome of management and as statements of accountability. They do not prescribe interventions, but can be used as benchmarks of current performance and can be used then to set targets for future performance against which progress can be assessed. The actual critical values for NUE and the targets to be established are aspects of policy, and are likely to vary from region to region and between farming systems.

An increase in NUE does not always guarantee lower N pollution, but it is an essential step for reducing N loss to the environment while maintaining high agricultural productivity. Our recommendation is based on the premise that using NUE as an indicator will likely reduce N losses to the environment, which will be followed in time by improved indicators of environmental quality, albeit with lags in the system. Hence, NUE should be viewed not as a final indicator of success, but rather an important and essential indicator of progress in the agricultural sector.

While NUE can be estimated using existing data and applied at a range of scales, it is a ratio and so does not provide a link to either productivity or soil health, both of which are critically important for current and future food security. In assessing progress to improved nutrient performance, both productivity (such as yield) and soil health (such as soil test values) should be considered as part of a suite of outcome indicators. Additionally, other indicators of the development of the support for and the adoption of sustainable crop nutrition (e.g. outreach to farmers) could extend the range of metrics appropriate to nutrient stewardship.

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Appendix Table: Cereal production NUE by country. Data were derived from FAOSTAT (Crop production and area sown), IFA (Fertilizer use by crop) and IPNI (Crop product nutrient concentrations). Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Cereal area (Mha)	Cereal production (Mt)	Mean cereal yield (t/ha)	NUE (kg N grain/kg N fert)	Output (kg N/ha)	Input (kg N/ha)	Surplus (kg N/ha)
Argentina	9.24	40.68	4.37	1.21	69.6	57.7	-12
Australia	18.37	26.45	1.39	1.02	27.9	27.4	-1
Bangladesh	11.18	46.95	4.02	0.57	55.1	96.6	41
Brazil	18.42	67.16	3.63	0.88	47.8	54.3	7
Canada	15.95	47.11	3.26	0.89	59.0	66.4	7
Chile	0.59	3.58	6.41	0.63	104.6	167.4	63
China	83.14	473.94	5.48	0.47	83.9	178.9	95
Egypt	2.99	20.98	7.01	0.45	113.0	252.1	139
EU-27	58.04	277.82	4.85	0.90	92.1	102.5	10
India	99.24	255.31	2.56	0.43	40.8	95.0	54
Indonesia	15.13	75.43	4.62	0.59	63.8	107.3	44
Iran	8.70	22.33	2.47	0.71	48.5	68.3	20
Malaysia	0.67	2.39	3.52	0.37	46.3	124.6	78
Mexico	10.01	33.54	3.36	0.62	48.9	79.3	30
Morocco	5.59	8.54	1.60	1.52	31.6	20.7	-11
Pakistan	12.93	33.92	2.58	0.38	47.9	126.0	78
Philippines	6.73	21.78	3.21	0.90	41.1	45.7	5
Russia	40.54	68.06	1.87	1.78	38.2	21.4	-17
South Africa	2.99	12.07	3.65	0.66	54.9	83.3	28
Thailand	11.32	37.27	3.00	0.90	42.5	47.4	5
Turkey	13.04	33.70	2.68	0.81	53.2	65.7	13
USA	52.86	370.00	6.69	0.64	95.6	149.8	54
Vietnam	8.36	42.16	4.96	0.60	65.1	107.6	43
World	679.08	2,355.31	3.43	0.68	55.7	81.4	26