Nitrogen Use Efficiency, Nitrogen balance, and Nitrogen productivity – a combined indicator system to evaluate Nitrogen use in crop production systems

Frank Brentrup[1], Joachim Lammel[1]

[1] Yara International, Research Centre Hanninghof, Hanninghof 35, 48249 Duelmen, Germany, www.yara.com, frank.brentrup@yara.com

Abstract

Several indicators are discussed to evaluate nitrogen use in agricultural production. Nitrogen use efficiency (NUE) can be defined as the ratio between N applied and N removed by the crop. NUE is, however, only one aspect of sustainability of N use. To account for environmental risks due to excess N, N balance (N input - N output) is seen as an appropriate indicator for N losses to the environment. While NUE and N balance focus on resource use efficiency and environmental pollution, the main purpose of agricultural production is providing food. It is therefore important to include the productivity dimension into the considerations, which can be crop N yield (crop yield * N content of the harvested product). The indicator system presented here considers these three important aspects of N use at the same time, i.e. resource use efficiency (NUE), environmental risk (N balance), and productivity (N output). All parameter can be derived from the same base data, N input and N output. Even more important as the way of calculation is the interpretation of the results. Examples from field trials show that very high as well as low NUE values may represent unsustainable systems and that the interpretation of NUE values requires a sound qualification scheme including acceptable boundaries for N balance and N output. This study explains (1) how the multi-dimensional indicator scheme works and how target values can be determined and (2) examines how agricultural practices such as precision farming tools support farmers achieving the defined targets.

Key Words

Nitrogen use efficiency (NUE), Nitrogen balance, crop production, N fertilizer

Introduction

Global food production relies on resources such as land, soil, water, biodiversity and plant nutrients. Inefficient use of these valuable and partly scarce resources is harmful to society and the environment. The need for plant nutrients in agriculture is large and expected to increase in the coming decades because of the increasing world population and anticipated changes in food consumption patterns. This is why communication about resource use efficiency and measures to increase efficient use of nutrients is needed. This holds especially for nitrogen. Nitrogen (N) is essential for life and needed in relatively large quantities for the production of amino acids (protein), nucleic acids and chlorophyll in plants. However, oversupply of nitrogen creates N pollution is therefore damages the environment.

Nitrogen use efficiency (NUE) is an indicator that can help to quantify and communicate the utilization efficiency of N in agriculture and food production. In principle, NUE calculation aims to quantify the fraction of the applied nitrogen that is taken up by the crop. Different methods for calculating NUE are currently used (Dobermann, 2007), which complicates further analyses and comparisons. Therefore, there is a need for a commonly accepted definition of NUE and a commonly accepted method for calculating NUE, which can be used in practice. The EU Nitrogen Expert Panel developed an easy-to-use indicator scheme for NUE, which evaluates NUE of agricultural systems in relation to their productivity (N yield) and potential N losses to the environment (N surplus; EU Nitrogen Expert Panel, 2015). This paper describes the combined indicator system in general, its graphical representation and an application to crop production for illustration.

Methods

In order to make it applicable to as many regions as possible, the combined indicator scheme solely relies on data about N input and N output of the agricultural production system under investigation. It depends on the scope of the analysis which input and output items are to be included in the calculations. The scope can range from a single crop grown on a specific field to whole food production-consumption systems of a country or region. Table 1 gives the N input and N output items to be considered for the proposed indicator system.

Table 1: Input and output items considered for the NUE indicator system (EU Nitrogen Expert Panel, 2015)

N input	N output
Mineral fertilizers	Crop products
Feed and fodder (net)	Animals (net)
Biological nitrogen fixation	Animal products (milk, egg, wool)
Atmospheric N deposition	
Compost and sewage sludge	
Seed and planting material	
Bedding material (straw, saw dust)	
Animal manure (net)	

The N input and output data are used to derive three different indicators at the same time:

1. Σ (N output) / Σ (N input) *100 = NUE (%) -> Indicator for *resource use efficiency*
2. Σ (N output) = N yield (kg N/ha) -> Indicator for *productivity*
3. Σ (N input) – Σ (N output) = N surplus (kg N/ha) -> Indicator for *potential N loss to the environment*

All three indicators are then combined into a two-dimensional input – output diagram that allows assessing performance of agricultural production in relation to all three dimensions. In order to effectively describe the agricultural production system under investigation, it is necessary to define benchmarks for each indicator. These benchmark values shall represent desirable and achievable targets for its productivity (N yield), resource use efficiency (NUE), and risk of environmental pollution (N surplus). Figure 1 shows the graphical representation of the indicator system with provisional benchmark values.

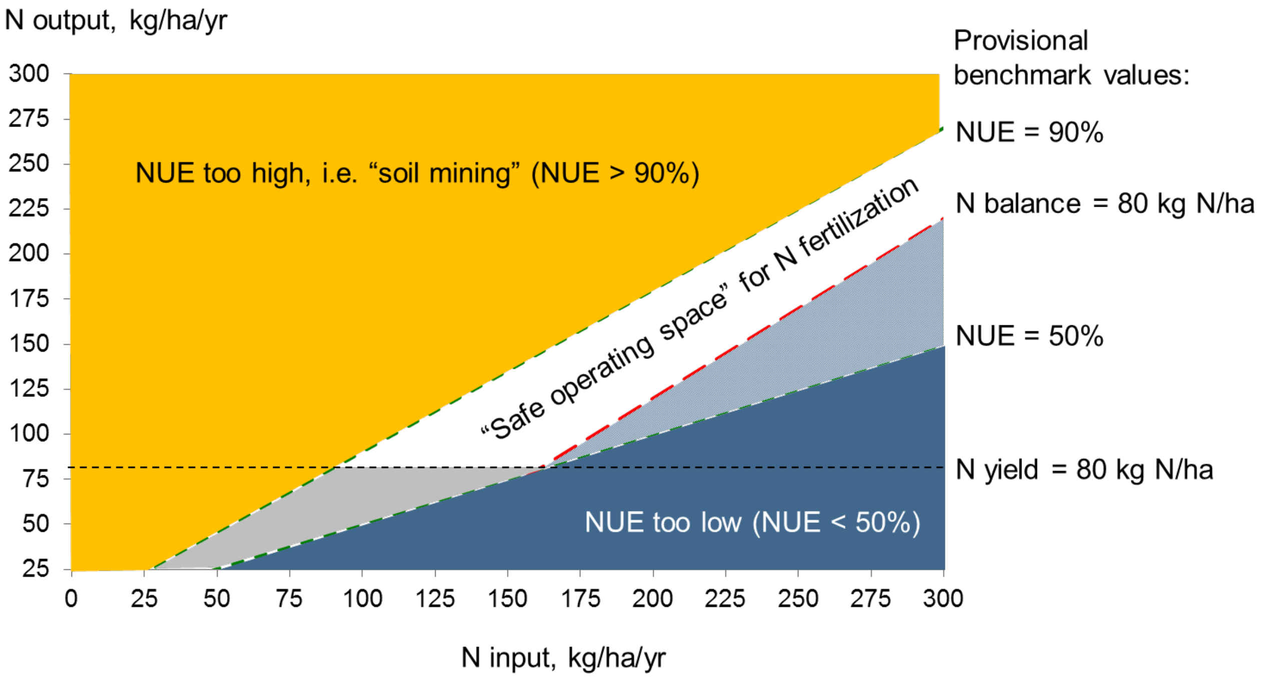


Figure 1: Conceptual framework of the combined NUE indicator system. The numbers shown are illustrative and will vary according to context (soil, climate, and crop). The slope of the diagonal wedge represents a range of desired NUE between 50% and 90%: lower values exacerbate N pollution (dark blue area) and higher values risk mining of soil N stocks (orange area). The horizontal line illustrates a desired minimum level of productivity (grey area). The additional diagonal defines a limit related to maximum N surplus to avoid N losses (light blue area). The combined criteria serve to identify a kind of "safe operating space" for N fertilizer management (white area).

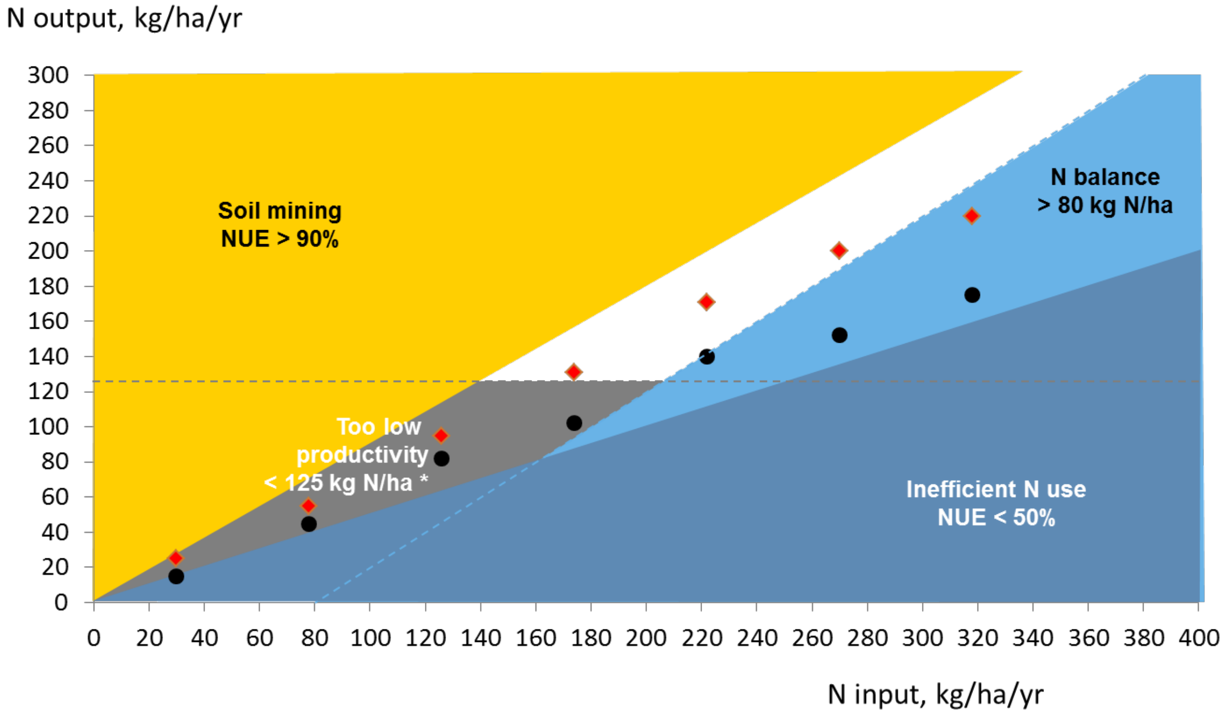
This methodology can for instance be applied to analyze different N fertilizer management options. We have applied the concept to two examples.

(1) Winter wheat grown at different N rates in a long-term experiment (Broadbalk Experiment, Rothamsted/UK) as monoculture wheat and in a rotation with other crops.
(2) Winter wheat grown at different N rates in one-year field trials (Yara R&D, Hanninghof/DE) with focus on economic optimum N fertilization by best practice nitrogen fertilizer recommendation

In both cases mineral N fertilizer and atmospheric N deposition (estimated by EMEP/MSC-W maps; http://webdab.emep.int/Unified_Model_Results/) were accounted for as N inputs and the N removed with grain as N output. Organic fertilizer was not applied and straw remained in the field after harvest. It was assumed that soil N stocks are in steady state due to long-term arable cultivation at all sites.

Results

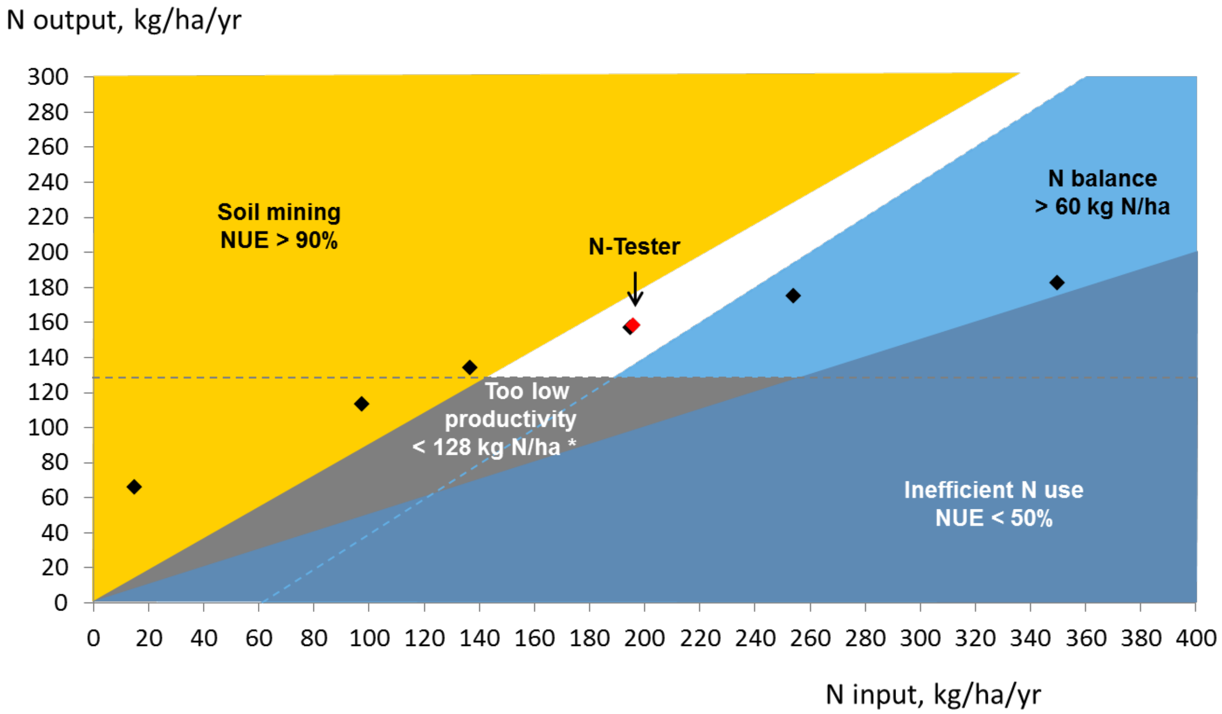
Figure 2 shows the results for the long-term Broadbalk experiment at Rothamsted (UK) for the period 1996-2012 (N input/output data from EU Nitrogen Expert Panel, 2015). The graph shows the result of two sub-trials both with winter wheat grown at increasing N rates: (1) in a rotation (red symbols), and (2) grown as monoculture wheat (black symbols). The calculation indicates that the provisional benchmark values for NUE and N surplus are achievable and realistic for well managed ‘high input - high output’ winter wheat cultivation in a rotation. In this case high N inputs (up to 270 kg N/ha) can go along with high N outputs and N surpluses of less than 80 kg N/ha. The target value for productivity (N output) needs to be defined specifically by crop and region and we suggest to use the average yields of a region or country. The benchmark value for N output was therefore set 125 kg N/ha which corresponds to the average wheat yield in the UK in 2011-2013. The result also shows the importance of good agricultural practices, in this case crop rotation, for achieving high NUE, high N output, and low N surplus, simultaneously.



* 7.26 t/ha * 0.86 * 20 kg N/t (avg. wheat yield in UK in 2011-2013, FAOSTAT database (2016)

Figure 2: Application of the NUE indicator scheme to winter wheat grown at different N rates in a long-term experiment (Broadbalk Experiment, Rothamsted/UK) as monoculture wheat (black circles) and in a rotation with other crops (red diamonds).

Figure 3 shows the data of an average yield response to increasing N fertilizer rates. It is calculated as an average of 189 one-year N response trials with winter wheat conducted on farmer fields all over Germany (2003-2015). Grain yield and N content were measured and converted into N output at six different N application rates ranging from 0 to 335 kg N/ha. An additional treatment was fertilized according to the Yara N-Tester recommendation for winter wheat in Germany. The N-Tester is a chlorophyll meter that is used for in-season plant monitoring and N fertilizer management. The total N input includes mineral N fertilizer application plus an additional amount of 15 kg N/ha, which is the average total N deposition rate in Germany in 2014 (EMEP, 2016). The graph clearly illustrates the challenge for the farmer to apply the right level of N fertilization to meet all benchmarks set in this example. At low N input (up to 140 kg N/ha) the modern wheat varieties exceed NUE of 90% i.e. impairing soil fertility in the long-term. At high N input (> 250 kg N/ha) there is increasing risk of N losses to the environment and also of non-compliance with possible future environmental regulation in Germany (acceptable field N balance of 60 kg N/ha). In this example the optimum N input is at about 200 kg N/ha. With this N rate the farmer hits the narrow white area of “safe operating space” for N fertilization. The N-Tester treatment is at the same level of N input, thus showing the usefulness of this precision farming tool in assisting farmers in N fertilizer decisions.



* 7.45 t/ha * 0.86 * 20 kg N/t (avg. wheat yield in DE in 2011-2013, FAOSTAT database (2016)

Figure 3: Application of the NUE indicator scheme to winter wheat grown in one-year experiments (n=189) at different N application rates on farmer fields in Germany (2003-2015)

Conclusion

The proposed NUE indicator system and its graphical representation is a simple, useful and flexible concept. It examines NUE in relation to N output and N balance, which are equally important indicators representing productivity and environmental impact of agricultural production systems. The scheme allows analyzing differences not only between fertilization schemes but also between farms, between specific systems, between countries, and between years. In this study we have focused on fertilization trials. The proposed indicator scheme allows assessing agricultural production systems in terms of resource use efficiency, productivity, and environmental impact at the same time. The examples of wheat production at different N fertilizer application rates reveal that too low as well as too high N rates may lead to unsustainable situations. Good agricultural practices such as crop rotation and in-season plant monitoring support farmers in managing N fertilizer in a more sustainable manner. Thus, the combined N indicator concept is an important tool to develop and steer N fertilizer management towards a sustainable direction.

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