

## **Nitrogen Use Efficiency (NUE)**

- **an indicator for the utilization of nitrogen in agriculture and food systems**



Prepared by the EU Nitrogen Expert Panel

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The report is available on-line at: [www.eunep.com](http://www.eunep.com)

**About EU Nitrogen Expert Panel**

*Key persons from science, policy and industry communities in Europe have been invited by Fertilizers Europe to establish the EU Nitrogen Expert Panel. The general objective of the Expert Panel is to contribute to improving NUE in food systems in Europe, through (i) communicating a vision and strategies on how to improve Nitrogen Use Efficiency in agriculture and food systems in Europe; (ii) generating new ideas, and recommending effective proposals and solutions; and by (iii) acting as referee in controversial issues, and (iv) by communicating with authority about nitrogen issues.*

*The Panel gathered for the first time in Windsor, United Kingdom on 15-16 September 2014, and agreed on a definition of NUE as indicator for agricultural productions at national scale, as presented here. There were 12 experts from science, 4 from policy and 3 from industry. They came from 9 EU countries. A second meeting at Chantilly, France, on 11-12 June 2015, served to develop consensus on the overall framing of the report, which was finalized during a third meeting at Amsterdam, 4 December 2015.*

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## Executive Summary

The main resources for global food production (land, soil, water, biodiversity, some nutrient elements) are finite and some even scarce. Moreover wasting resources is often harmful to society and the environment. The pressure on our natural resources is large, and at risk of increasing in the coming decades due to the projected increase in human population in the world and anticipated changes in food consumption patterns.

There is a need for communications about resource use efficiency and for measures to increase the use efficiency of nutrients in relation to food production. This holds especially for nitrogen. Nitrogen (N) is essential for life and a main nutrient element. It is needed in relatively large quantities for the production of amino acids (protein), nucleic acids and chlorophyll in plants. However, excess N pollution is a threat to our health and the environment.

The ambition of the EU Nitrogen Expert Panel is to contribute to improving efficient nitrogen use in food production. Here, we propose an easy-to-use indicator for 'nitrogen use efficiency' (NUE), applicable to agriculture and food production–consumption systems. It is based on the mass balance principle, i.e. using N input and N output data for its calculation:  $NUE = N \text{ output} / N \text{ input}$ . NUE values have to be interpreted in relation to productivity (N output) and N surplus (i.e., the difference between N input and harvested N output).

For estimating NUE and communicating the results, data and information are required about (i) the total N inputs into a system and the N output in harvested products, (ii) the nature of the system (e.g. farm, crop system, livestock housing system, food processing and distribution system) and its boundaries, (iii) the time span of the analyses, and (iv) possible changes in the stock of N in the system. The NUE indicator is easily presented via a two-dimensional input – output diagram. This allows the presentation of NUE, N output and N surplus in a coherent manner, together with possible reference or target values (Figure ES1).

The NUE concept is illustrated in this report with four different cases:

- a) for crops at the field scale, using data from four different N fertilization trials,
- b) for crop production systems for different EU Member States, based on data for the period 1961 to 2010,
- c) for the Gross Nitrogen Balance of agricultural soils for EU Member States, based on a replotting of data from OECD and Eurostat, and
- d) for mixed crop-livestock systems (dairy farms), where changes in NUE are analyzed over a 15 years period.

The final discussion chapter concludes that the NUE indicator proposed here is a simple, useful and flexible concept. It allows decision makers to examine differences in NUE between farms, between specific systems, between countries, and between years. Effects of technical progress and of policy measures can be identified. As such, NUE can serve as a valuable indicator for monitoring sustainable development in relation to food production and environmental challenges. By considering limits associate with both excess and insufficient N use, the NUE indicator contributes towards improving N

use efficiency in the food chain. For proper comparisons, a clear and approved protocol is needed for uniform data and information collection, processing and reporting.

Nitrogen use efficiency impacts many of the recently proposed/defined Sustainable Development Goals (SDGs) for the post-2015 era, for which concrete targets, pathways and indicators need to be developed at country scale and below. The proposed NUE indicator is suitable for setting realistic targets and monitoring of progress in that context, particularly in relation to SDG 2 (Food and nutrition security), SDG 12 (Sustainable consumption and production), SDG 14 (Marine ecosystems) and SDG 15 (Terrestrial ecosystems).

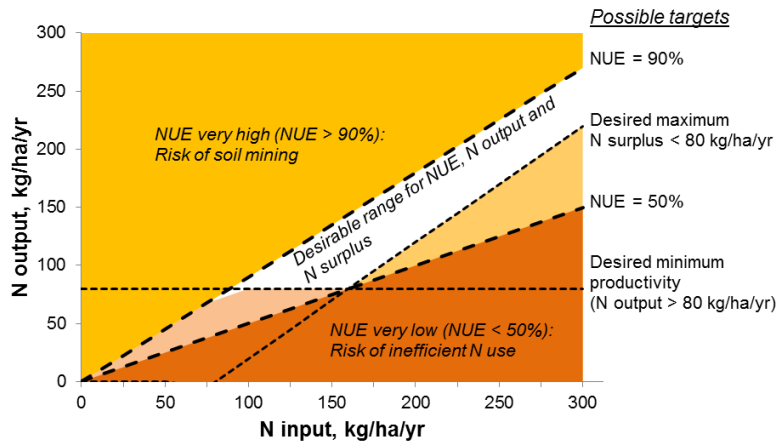


Figure ES1. Conceptual framework of the Nitrogen Use Efficiency (NUE) indicator. The numbers shown are illustrative of an example system and will vary according to context (soil, climate, crop). The slope of the diagonal wedge represents a range of desired NUE between 50% and 90%: lower values exacerbate N pollution and higher values risk mining of soil N stocks. The horizontal line is a desired minimum level of productivity for the example cropping system. The additional diagonal represents a limit related to maximum N surplus to avoid substantial pollution losses. The combined criteria serve to identify the most desirable range of outcomes.

## 1. Introduction

Nitrogen (N) is essential for life and plays a key role in food production. Nitrogen is the most important crop-yield limiting factor in the world, together with water (Mueller et al., 2012). That is why farmers apply N fertilizers, which became available and affordable in affluent countries from the 1950s and more recently in almost all countries (Smil, 2000). However, too much N leads to pollution, which is harmful for the functioning of our ecosystems and our health (Box 1). The management of N is therefore important, especially in agriculture, which is the biggest user of N in the world. Nitrogen management in agriculture aims at achieving agronomic objectives (farm income, high crop and animal productivity) and environmental objectives (minimal N losses) simultaneously. However, N management is not easy, because the N cycle is complex (Box 2) and N is easily lost from agriculture into the environment.

Indicators play a key role in management and policy (Box 3). Indicators need to have an analytically sound basis and sound underpinning, because managers and policy makers need reliable data and information and robust tools to be able to make the right analyses, decisions and actions. Nitrogen use efficiency (NUE) is a key indicator in agriculture, but currently there is no uniform and robust methodology and protocol for its estimation and use. Several studies have estimated NUE in crop production, animal production and in whole food systems, but these studies often use different concepts, different system boundaries, different scales, different input data and use different assumptions. So far most studies have been undertaken in crop production (e.g., Mosier et al., 2005; Ladha et al., 2005; Dobermann 2005, 2007; Johnston and Poulton, 2009; Fixen et al., 2014). Annex 1 provides an overview of common NUE indicators in crop production at field scale. In animal production, the emphasis has been often on the feed conversion ratio, i.e., the amount of feed needed to produce a unit of animal produce. Other studies have examined the fraction of feed N converted into protein N in milk, meat or egg (e.g., Nevens et al., 2005; Powell et al., 2010; Bai et al., 2014). Further, there is interest in NUE of food systems, of the whole food production – consumption chain (e.g., Bleken and Bakken, 1997; Galloway and Cowling, 2003; Ma et al., 2012; 2014; Sutton et al., 2013). There is also an interest in developing economy-wide NUE indicators, to enable the contributions of different economic sectors to be recognized, which is an area being pioneered by the OECD (Bleeker et al., 2013).

Different definitions and different methods for estimating NUE lead to different outcomes, which complicates the making of useful further analyses and comparisons. Evidently, there is a need for a commonly accepted definition of NUE and a commonly accepted method for estimating NUE, which can be used in practice.

The purpose of the study reported here was to derive and approve an easy-to-use indicator for NUE (definition and method) to be used by practice and policy for estimating NUE. Given the mandate of the EU Nitrogen Expert Panel, the report focuses on agriculture and food systems. However, the work also contributes towards parallel developments in defining economy-wide NUE indicators. The NUE indicator proposed here can be used for all agricultural and food systems. The uniform and easy-to-apply concept allows to make comparisons between systems, but also between countries, and between years for specific systems. The NUE indicator provides also the opportunity to estimate the possible gap between actual NUE and an attainable (or target) NUE, based on for example best management practices or on the average values obtained in well-managed field experiments. This report presents the concept and underpinning of the NUE indicator.

**Box 1. Nitrogen is essential for life but too much nitrogen is harmful**

Nutrient elements are essential resources for food, feed and biofuel production, next to energy, carbon dioxide, water, biodiversity, labour, capital and management. Plants require 14 nutrient elements, in specific amounts, for proper growth and development. Animals and humans require some 22 nutrient elements in specific quantities, for proper growth and development.

Nitrogen (N) is a main nutrient element and needed in relatively large quantities for the production of amino acids (protein), nucleic acids and chlorophyll in plants. Nitrogen occurs in different forms in soil, air and waters, but only a few N forms are directly available for uptake by plant roots. The availability of N is often limiting food, feed and biofuel yields; it is one of the elements that is most limiting biomass production in the world.

The invention of the Haber-Bosch process, more than 100 yrs ago, marks a major change in the global N cycle, as it allowed the large-scale production of synthetically produced N fertilizers from di-nitrogen ( $N_2$ ) in the atmosphere. Relatively cheap N fertilizers came on the market from about the 2<sup>nd</sup> half of the 20<sup>th</sup> century, especially in affluent countries. The increased use of N fertilizers has contributed greatly to the increased global food, feed and biofuel production, needed for the increasing human and animal populations (Smil, 2000).

Global N fertilizer use has increased from about 10 Tg in 1961 to almost 110 Tg in 2012 (Figure 1), but there are large differences between continents. Fertilizer N use in Africa is staggering at a level of about 1-2 Tg per year during the last decade, while fertilizer N use in Asia has increased during last three decades by on average 2 Tg per year. Fertilizer N use in Europe increased fast between 1950 and 1990, but stabilized thereafter at a level of about 10 Tg per year (Erismann et al., 2008; Sutton et al., 2011; Sutton et al., 2013). The rapid decrease in European N use around 1990 is mainly due to the political restructuring of Eastern and Central Europe at this time. The slow decrease in fertilizer use in Europe between 1990-2010 is related also to EU agri-environmental policy.

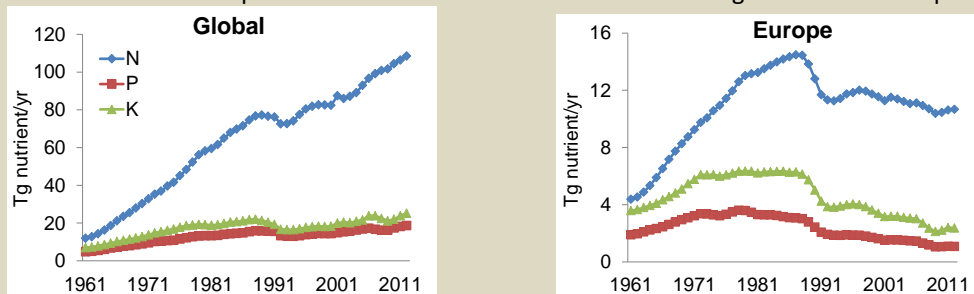


Figure 1. Changes in Fertilizer N, P, K use in the world and Europe during 1961-2011 (FAOSTAT, 2015)

The availability of N in agriculture increased during the last 100 yrs also through the production of leguminous crops (beans, pulses, clover and alfalfa) that fix  $N_2$  biologically, through energy combustion that increases atmospheric  $NO_x$  emissions and N deposition, and through the increasing production of animal manures, and of residues and wastes from industries and households (Herridge et al., 2008; Davidson, 2009; Sutton et al., 2013).

The increased availability of N in agriculture has also increased the losses of N to the wider environment, to air and water bodies. Emissions of N to the wider environment occur via various N forms (Box 2; e.g.,  $NH_3$ ,  $N_2$ ,  $N_2O$ ,  $NO$ ,  $NO_3^-$ ), which can lead to problems related to human health and ecosystem degradation. The volatilization of ammonia ( $NH_3$ ), leaching of nitrate ( $NO_3^-$ ), and the emissions of di-nitrogen ( $N_2$ ), nitrous oxide ( $N_2O$ ) and nitrogen oxide ( $NO$ ) following nitrification-denitrification reactions are the main N loss pathways from agricultural systems and food systems. These N forms (except  $N_2$ ) are often termed “reactive N”, as they are biologically, photochemically and/or radiatively active N compounds. Possible human health and environmental effects of this reactive N include (Galloway et al., 2008; Sutton et al., 2011) a decrease of human health, due to  $NH_3$  and  $NO_x$  induced formation of particle matter ( $PM_{2.5}$ ) and smog, plant damage through  $NH_3$  and through  $NO_x$  induced tropospheric ozone formation; a decrease of species diversity in natural areas due to deposition of  $NH_3$  and  $NO_x$ ; acidification of soils because of deposition of  $NH_3$  and  $NO_x$ ; pollution of groundwater and drinking water due to nitrate leaching; eutrophication of surface waters, leading to algal blooms and a decrease in species diversity; global warming because of emission of  $N_2O$ ; and stratospheric ozone destruction due to  $N_2O$ .



### Box 2. The Nitrogen Cycle

Nitrogen (N) occurs in different forms and transforms from one form into the other almost endlessly (Figure 2). Molecular nitrogen ( $N_2$ ) is the dominant constituent of our atmosphere and the most abundant N form on Earth. Only a few microorganisms have the capability to utilize (fix)  $N_2$ , converting it to organically bound N. The Haber-Bosch process converts  $N_2$  into ammonia/ammonium ( $NH_3/NH_4^+$ ) in a physical-chemical manner. The  $NH_3/NH_4^+$  can be taken up by plants (assimilation). Following the senescence of plants and organisms, the organic-N is transformed again into  $NH_3/NH_4^+$  (through mineralization). Autotrophic bacteria can utilize the energy contained in  $NH_3/NH_4^+$  through nitrification. Thereby, the oxidation status increases from -3 in  $NH_3/NH_4^+$  to +5 in nitrate ( $NO_3^-$ ). The  $NO_3^-$  can be taken up by plants (assimilation) or it is denitrified to nitrous oxide ( $N_2O$ ) and to di-nitrogen ( $N_2$ ) in anaerobic environments through heterotrophic bacteria. Molecular N ( $N_2$ ) may be formed also through anaerobic ammonium oxidation (anammox;  $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$ ), by chemoautotrophic bacteria in the deep sea.

Figure 3 presents a quantitative picture of the global N cycle. Large amounts of N cycle between atmosphere and the terrestrial and marine biospheres, via gaseous N forms.

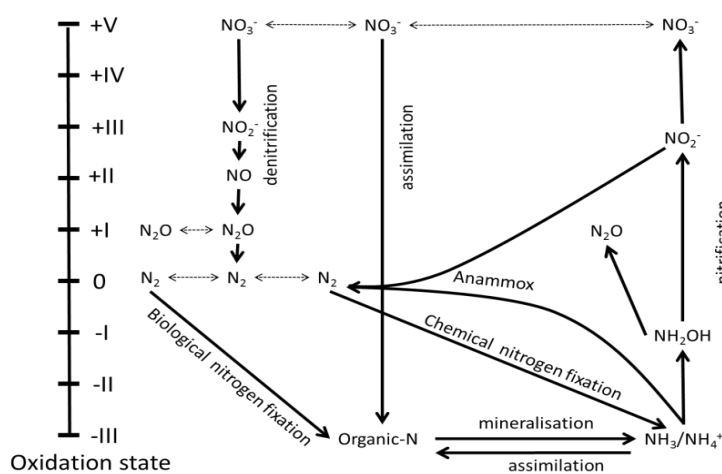


Figure 2. Processes of the N cycle and the related changes in the oxidation status of the N forms. The oxidation status (vertical axis) ranges from +5 in nitrate ( $NO_3^-$ ) to +3 in nitrite ( $NO_2^-$ ), to +2 in nitrogen oxide ( $NO$ ), to +1 in nitrous oxide ( $N_2O$ ), to 0 in di-nitrogen ( $N_2$ ), and -3 in ammonia ( $NH_3$ ), ammonium ( $NH_4^+$ ) and amines ( $C-NH_2$ ). The N forms  $NH_3$ ,  $N_2$ ,  $N_2O$ ,  $NO$ ,  $NO_x$  are gaseous at temperature at the earth surface; the N forms  $NO_3^-$  and  $NH_4^+$  and some organic N forms (DON) are readily soluble in water. This makes N 'double mobile' (Smil, 2000)

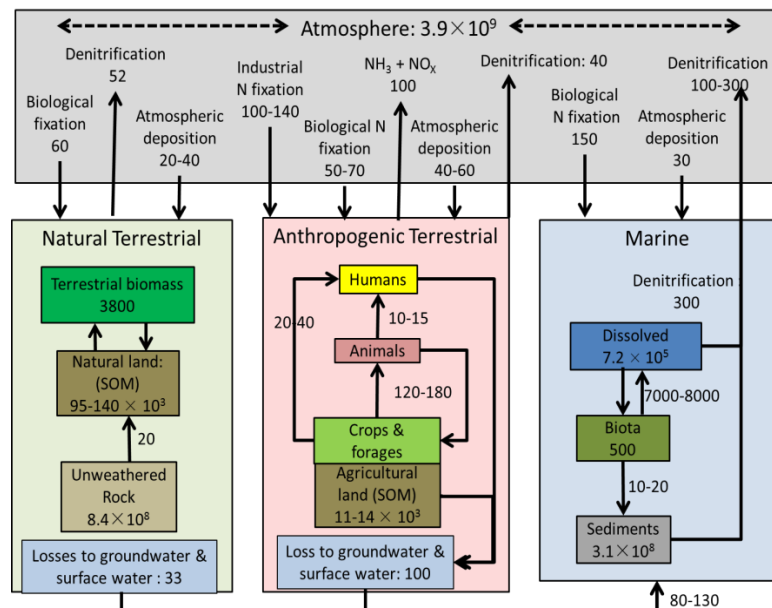


Figure 3. Global nitrogen cycle, showing the dominant flows of N between atmosphere and the natural terrestrial area, the anthropogenic area (agricultural + industrial + urban), and the marine area. Arrows indicate the approximate size of the N flows, in Tg N per yr. Numbers in boxes refer to the size of the N pool of that compartment, in Tg N. Note that the transport of N from anthropogenic sources to the natural terrestrial and marine areas occurs mainly via the atmosphere and rivers. The magnitude of some flows are rather uncertain. Compilation of data from Smil (2000), Fowler et al (2013), Schlesinger and Bernhardt (2013).

### Box 3. Role of policy measures and indicators

A range of policy measures have been introduced in the European Union to minimize the emissions of N from agriculture to the environment, from the beginning of the 1990s onwards. Some of these policy measures have been effective, while the impacts of others are delayed (Sutton et al., 2011). These agri-environmental policies have become increasingly integrated in the Common Agricultural Policy of the EU from 2005 through the cross compliance regulation and rural development program, and, from 2014, also through the greening of the Common Agricultural Policy. These policy developments indicate that nitrogen is at the core of two major societal issues, namely food production and security, and environmental sustainability.

Forecasts have indicated that more food, feed, fiber and biofuel will be needed during next few decades, because of the increasing human population, changing diets and the development of a more bio-based economy (Alexandratos and Bruinsma, 2012). Though the number of people and the animal-derived protein content in the diets in the European Union (EU) will likely not increase much in next decades, Europe will likely feel the increasing pressure on resources, resulting from a globalizing world. Good quality soil, water, biodiversity and various nutrient elements are all finite resources, and there are competing claims on these resources in the world.

Ensuring sustainable food, feed and biofuel production systems therefore demands for increasing resources use efficiency and less wasting (SDSN, 2013). In *“Towards a circular economy: A zero waste program for Europe”* (COM, 2014, 398), the European Commission states that efforts are needed to increase resource use efficiency, and that improvements in resource efficiency can bring major economic and environmental benefits.

Earlier, the European Commission promoted *‘The Bioeconomy Strategy’* (COM, 2012, 60) for the sustainable and integrated use of biological resources and waste streams for the production of food, energy and bio-based products. Both the Circular Economy Strategy and the Bioeconomy Strategy contribute to the objectives of the Europe 2020 flagship initiatives "Innovation Union" and "A Resource Efficient Europe" (COM, 2011, 21). Improving resource efficiency is also seen as an opportunity to keep costs under control by reducing material and energy consumption, and to boost competitiveness.

Evidence-based, robust targets and indicators are needed for monitoring progress towards achieving the new Sustainable Development Goals (SDGs), including achieving a high resource use efficiency (SDSN, 2015). Such indicators have to be derived in a uniform and easy-to-use manner to allow unbiased comparisons, to streamline and facilitate national-level data collection and reporting, and to increase the reliability of data and its consistency.

Adopting common indicators will also facilitate better monitoring and benchmarking of performances by industry and policy. Table 1 list the 28 main agri-environmental indicators used by EUROSTAT and EEA for evaluating agri policy measures in EU-28. Relevant indicators for this report have been highlighted (in blue).

Table 1. The 28 Agri-environmental indicators (AEIs). [COM\(2006\) 508](#)

No	Indicator title (AEI)	No	Indicator title (AEI)
1	Agri-environmental commitments	14	Risk of land abandonment
2	Agricultural areas under Natura 2000	15	Gross nitrogen balance
3	Farmers' training levels	16	Risk of pollution by phosphorus
4	Area under organic farming	17	Pesticide risk
5	Mineral fertiliser consumption	18	Ammonia emissions
6	Consumption of pesticides	19	Greenhouse gas emissions
7	Irrigation	20	Water abstraction
8	Energy use	21	Soil erosion
9	Land use change	22	Genetic diversity
10.1	Cropping patterns	23	High nature value farmland
10.2	Livestock patterns	24	Production of renewable energy
11.1	Soil cover	25	Population trends of farmland birds
11.2	Tillage practices	26	Soil quality
11.3	Manure storage	27.1	Water quality - Nitrate pollution
12	Intensification/ extensification	27.2	Water quality - Pesticide pollution
13	Specialisation	28	Landscape - State and diversity

## 2. Concept of Nitrogen Use Efficiency (NUE)

We propose an easy-to-use NUE indicator, applicable to all agricultural systems<sup>1</sup> and food systems<sup>2</sup>. The concept for NUE use here is based on the mass balance principle (Figure 4), i.e. using N input and N output data for its calculation:  $NUE = N \text{ output} / N \text{ input}$ .

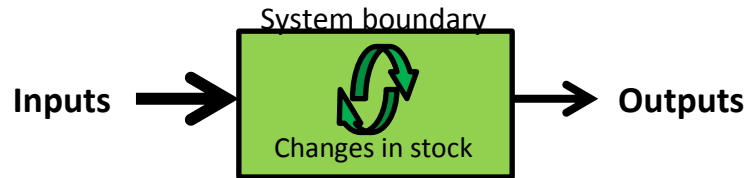


Figure 4. Concept of an input – output mass balance of a system. Total inputs must balance total outputs, following corrections for possible changes in storage within the system. Note that (N) losses are not shown in this figure.

Agricultural and food systems are N-leaky, i.e., there are many opportunities for N species to escape (Figure 5). Hence, the input – output mass balance of food systems is in reality more complicated than presented in Figure 4. However, the principle of the mass balance remains the same, irrespective of the system. In agricultural systems, only a fraction of the N input ends up in the harvested products; the remainder is dissipated into the atmosphere or water bodies or is accumulated in the system (temporarily). The mass balance reads in this case as  $N \text{ input} = N \text{ output} + N \text{ losses} + \text{changes in stocks}$ .

The NUE indicator presented here addresses the N outputs in harvested produce only. For crop production systems, the N output in harvested crop removed from the land is considered. For animal production systems, the N output may be milk, meat, egg and/or wool. For mixed production systems, both crop and livestock products are included.

Hence,  $NUE = N \text{ output in harvested products} / N \text{ input}$ .

NUE depends on the system and its management; NUE increases as the N output in harvested products increases and/or the N input decreases. Conversely, NUE is low when the N output in harvested products is relatively low and the N input relatively high.

<sup>1</sup> Agriculture encompasses all activities related to crop and animal production. An agricultural or farming system is commonly defined as a population of individual farms that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate. Depending on the scale of the analysis, a farming system can encompass a few dozen or many millions of households. A main distinction is commonly made between (i) specialized crop production systems, (ii) specialized animal production systems, and (iii) mixed production systems (<http://www.fao.org/farmingsystems>).

<sup>2</sup> A food system includes all activities involving the production, processing, transport and consumption of food. Agriculture is therefore a part of a food system. A food system also includes the inputs needed and outputs generated at each of these steps. A food system operates within and is influenced by social, political, economic and environmental contexts.

Many combinations are possible, but the ideal case is often a high N output via harvested products combined with a high NUE and a low N surplus (difference between N input and N output). Hence, for proper interpretation, NUE should be reported together with the N output in harvested products (as indicator for the productivity of the system), and the N surplus (as proxy for the potential N loss to the environment). In addition, there should be information about the possible accumulation or depletion of N in the system. For example, N output in harvested products can be high for a few years, while N inputs are temporarily reduced, due to mineralization (release) of soil N from within the system. The reverse is also possible: a low N output in harvested products at relatively high N input, due to accumulation of N in the system.

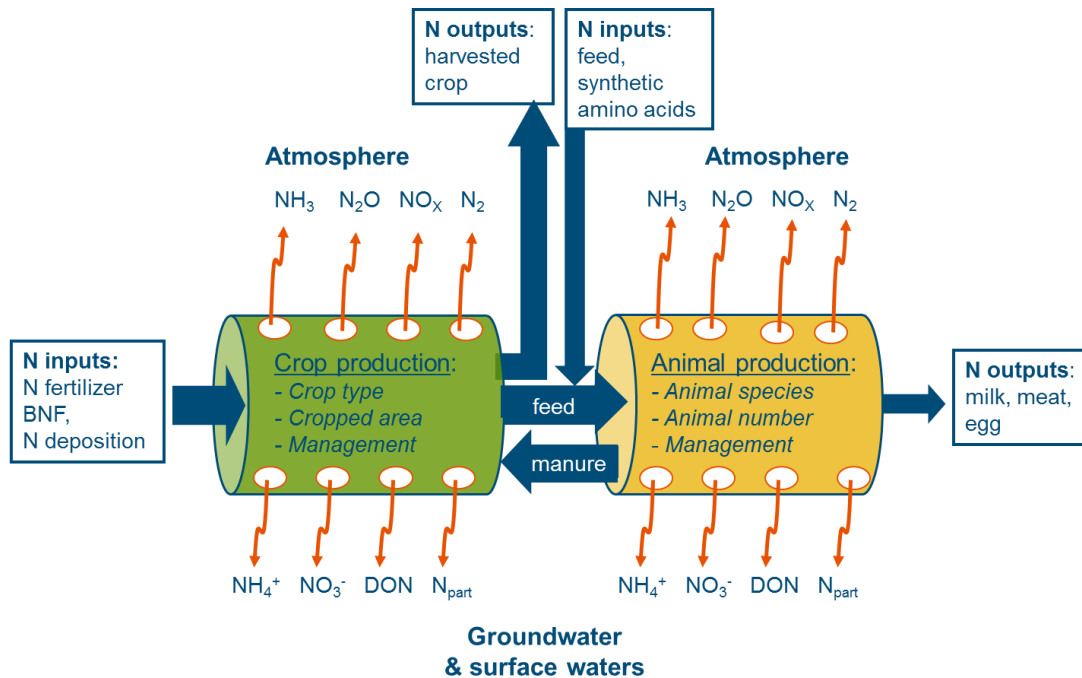


Figure 5. Concept of the nitrogen input – output mass balance of mixed crop – livestock production systems. The ‘hole of the pipe’ model illustrates the ‘leaky N cycle’ of crop and animal production; it shows the fate of N inputs in agriculture. Inputs, outputs in useful products and emissions to air and water show dependency in crop production and animal production; a change in the flow rate of one N flow has consequences for others, depending also on the storage capacity of the system. Total inputs must balance total outputs, following corrections for possible changes in storage within the system (Oenema et al., 2009)

The N output is used here as an indicator for the harvested yield. In many cases, N output is linearly related to harvested yield (the N content of the harvested crop is more or less independent of N input). However, in the case of leafy vegetables (e.g., spinach, lettuce) and herbage (grass), the N content of the harvested produce may increase with N input due to the accumulation of nitrate in the leaf tissue, depending also on harvesting stage. This ‘luxury N uptake’ in vegetables and some forages needs to be accounted for when setting crop specific target values for N output.

NUE depends on the agricultural system (or food system) and its management. In crop production systems, NUE depends on crop type and rotation, crop husbandry, soil fertility, type of N inputs (e.g., fertilizers versus animal manures, composts), and environmental conditions (climate, geomorphology, hydrology, etc.). In specialized animal production systems, NUE depends on animal category, breed, and productivity, feed quality, herd and feeding management, and environmental conditions (climate, animal housing). In mixed systems, NUE depends on a combination of the aforementioned factors.

NUE can be influenced by the externalization of (aspects of) the production processes, for example the production of seed and planting material, and the raising of young stock and/or the production of animal feed elsewhere. Externalization of production processes usually increases the apparent NUE, because part of the cost of the production is transferred to other systems. The net feed import into European agriculture is a good example here. Evidently, this externalization has to be reported, and this can also be addressed by defining the system boundaries according to the specific scale and purpose of assessment. An advantage of upscaling NUE across the whole food-chain or the wider-economy is that this allows more terms to be internalized in the assessment.

NUE is also influenced by the type of N inputs considered; in principle all N inputs must be considered, including atmospheric deposition, biological N<sub>2</sub> fixation, planting materials, crop residues, etc. In practice though, information about some inputs may be lacking or considered difficult to control. Therefore, the type N inputs considered must be reported, and comparisons between systems or between countries can only be made accurately when standardizing the type of N inputs that are considered.

NUE is influenced by the length of the period under consideration. For a crop production system, ideally a whole crop rotation should be considered. In animal production systems, the whole lifetime of an animal needs to be considered. This is because NUE depends on the type of crop and the stage of the animal production cycle, respectively. However, if systems are relatively stable over time, or represent averaging on larger scales (e.g. regional or national values), estimates can be made on an annual basis.

We recommend that NUE is reported as a percentage (%) or mass fraction (kg per kg, i.e. kg kg<sup>-1</sup>), while N input, N output in harvested produce, and N surplus are to be reported in kg ha<sup>-1</sup> yr<sup>-1</sup>.

The NUE indicator presented here is also applicable to whole food production – processing – consumption systems. Such a framing increases the number of stages to be considered, including the consequences of losses associated with transportation and storage of agricultural products, food waste and the consequences of choosing food products associated with different levels of resource efficiency (Figure 6). There are also more opportunities for recycling N that can increase the overall N use efficiency of the food chain (e.g. waste water nutrient recycling in addition to manure recycling). In this case NUE is again defined in terms of N output divided by N input (in conjunction with N output and N surplus), but the input and output terms are different. For example, the output of a whole food production – consumption system can be the N in food available for consumption, or even N in food actually consumed. The total N input into the whole food production – consumption system relates to the N flows that are entering the system from outside the system, i.e., the internal N flows and N recycling are not accounted for. NUE of a whole food systems is high if the system thrives on recycled N and therefore requires little N imports. Hence, the benefits of for example reducing food waste are

recorded in the NUE indicator because less external N is needed. The NUE indicator can be defined at the whole food chain level, but also at sector/compartment level, as well as across the whole economy.

Aggregated NUE approaches may offer advantages for data collection, because some information may be difficult to collect and not directly needed in these aggregated approaches, while the outcomes of improved N management are still recorded in the resulting indicator. For example in calculating NUE of the food chain, the N inputs include fertilizers, biological N fixation and atmospheric N deposition, while the outputs include food for humans together with possible other useful products (including export of food). Manure and wastewater are recycling terms and do not explicitly appear in the equation. By contrast, manure and wastewater become key N recovery and recycling opportunities, where improved processing implicitly increases the overall NUE of the food system, when this recycled N replaces N inputs via fertilizers and/or biological N fixation.

The spatial boundary of a food system is commonly a country, continent or region, and often depends on the availability of data and information from statistical offices. The development of an operational NUE indicator for the entire food system (including food waste, food choice) and across all sectors of the economy is ongoing.

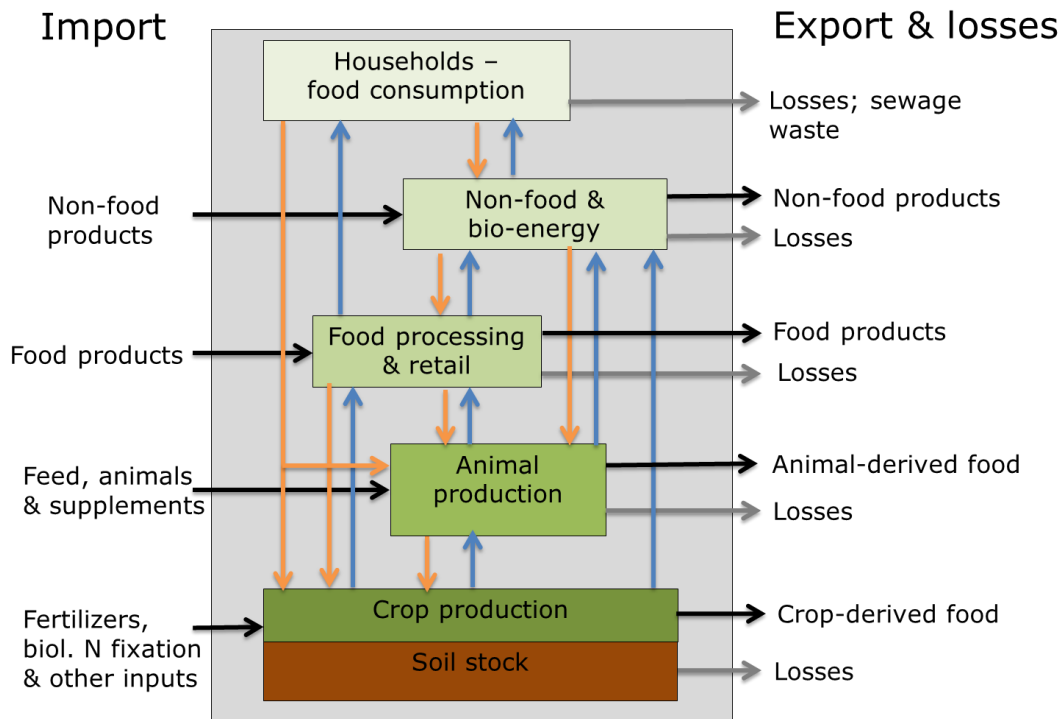


Figure 6. Schematic representation of N cycling in a food production – processing - consumption chain. Boxes inside the whole food chain (grey-colored box) refer to sectors (subsystems or compartments). Arrows indicate N flows. Arrows on the left-hand side of the food chain indicate N import (inputs), arrows on the right-hand side indicate exports (black arrows) and losses (grey arrows). Blue arrows inside the food chain indicate the upward flow of N embedded in food products. Orange arrows indicate the recycling of N embedded in residues and wastes (after Ma et al, 2012, 2013; Van Dijk et al., 2016).

### 3. A graphical presentation of NUE

A graphical presentation of N input and N output of any system allows the system performance to be assessed in relation to NUE and N surplus. It also allows changes over time in NUE to be shown, as well as N output, N input and N surplus. Moreover, it allows the deviation of an observed situation from possible NUE target or reference values to be indicated.

Figure 7 presents a two-dimensional input – output diagram of this form that allows system performance to be assessed in relation to NUE, N output in harvested produce and N surplus, together with possible target or reference values.

As  $NUE = N \text{ output} / N \text{ input}$ , the position of any system in relation to NUE is indicated by its deviation from the 1:1 line on this figure. Figure 7a shows how three zones for NUE are distinguished, namely a zone with low NUE values, a zone with a 'desired' range of NUE values, and a zone with high NUE values. The rationale of three zones is that both a 'too high' and 'too low' NUE are undesirable, especially over long time periods. A 'too low' NUE value indicates inefficient resource use and points to high N losses; a 'too high' NUE points to resource depletion, i.e., soil N depletion often termed 'soil nutrient mining'. Mining N (and other nutrients) from soils is a common phenomenon in rural areas in Africa; it leads to soil degradation, erosion and poverty (Sanchez, 2000). On the other hand, mining of nutrients from highly fertile soils in some affluent countries may be considered good practice, as it results in a high resource use and it may decrease potential nutrient losses.

While good management can reduce losses, in practice some N losses are inevitable. In the case of the example illustrated in Figure 7a for cropping systems, we therefore show an upper limit target value for NUE of 90%. The lower limit target value for NUE is here shown at 50%, being a value that has been shown to be achievable for average practices for many cropping systems. It should be noted that the exact position of the reference lines on Figure 7a are tentative. This is because the reference or target values depend on the type of agricultural systems (and food systems), as well as the environmental conditions (i.e., soils, geomorphology, climate). Setting of these target values is therefore a task that involves science, practice and policy domains.

This graphical approach can be extended to examine NUE in relation to N output in harvested produce and N surplus. As with NUE, possible target or reference values can be set for N output and N surplus.

The inclusion of a minimum N output as a target is illustrated in Figure 7b. The rationale for a reference value for N output is that some minimum yield level should be achieved, given the need to produce a desired amount of food, feed and biofuel, and for a farmer, region and country to be competitive. For the example cropping system in Figure 7b, we have illustrated a target N output value of 80 kg N per ha per year. The actual target N output in any situation will depend on the nature of the system being considered, such as the type of crop, the climate and soil type. In the case of livestock systems, a target minimum level of output will also depend on animal type, breed and the nature of the available animal feeds.

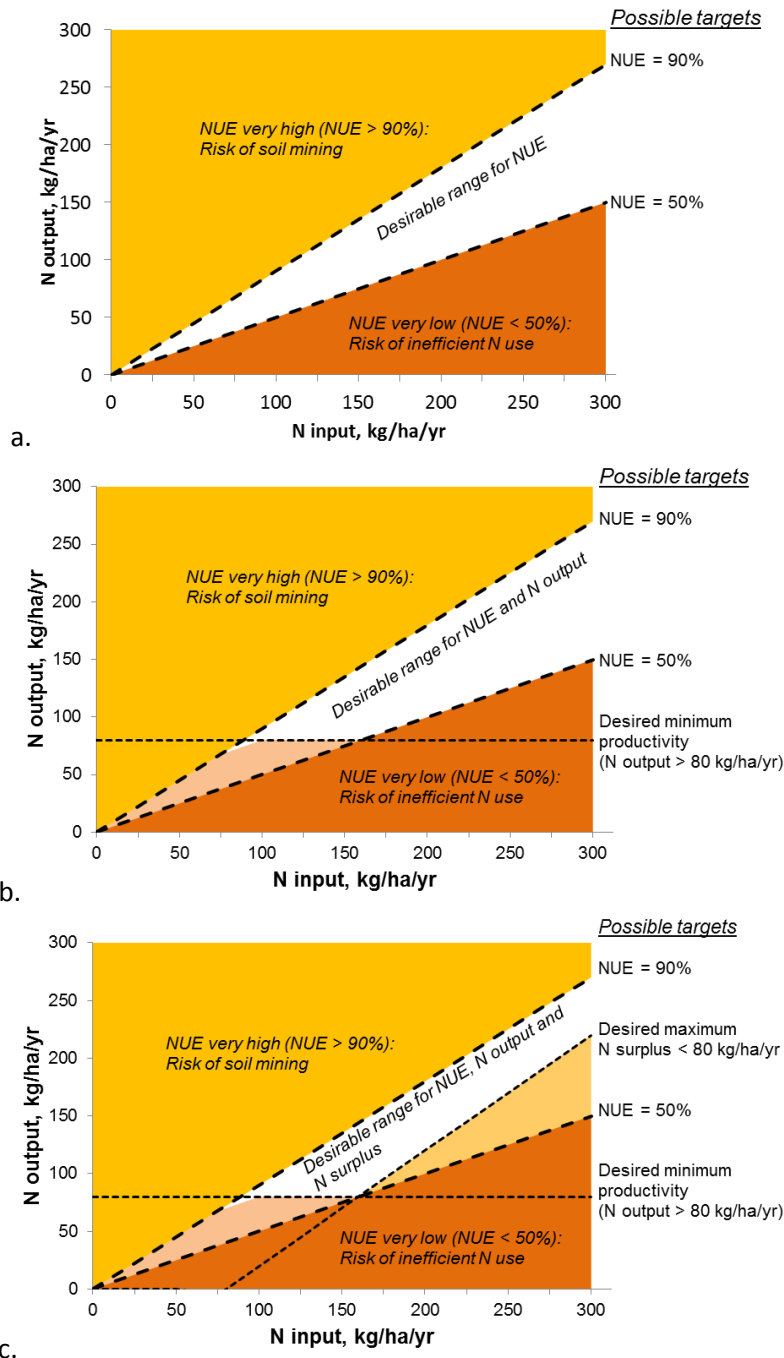


Figure 7. Concept of the NUE indicator; a two-dimensional N input – N output diagram. The upper panel shows three ranges of possible NUE values, based on possible reference values for NUE for cropping systems, i.e., 50 and 90%. The panel in the middle adds a minimum desired N yield level, in this case 80 kg/ha, and narrows the ‘desired’ range of NUE values. The bottom panel adds the constraint of N surplus, in this case set at 80 kg/ha, and thereby narrows the ‘desired’ range of NUE values further.



A third target value is shown in Figure 7c which indicates a maximum level of N surplus. The rationale for a target value for N surplus is that N surplus is a proxy for potential N losses to the environment and that threshold values for nitrate-N and total N in groundwater and surface water bodies should not be surpassed. Also, N losses via ammonia ( $\text{NH}_3$ ) volatilization and nitrous oxide ( $\text{N}_2\text{O}$ ) emissions to air have to be minimized, to be able to comply with  $\text{NH}_3$  and  $\text{N}_2\text{O}$  emission mitigation policies. Although environmentally benign, losses through di-nitrogen ( $\text{N}_2$ ) emission are also relevant as they represent a loss of energy invested in the system and tend to be associated with a higher level of  $\text{N}_2\text{O}$  emissions, through a process called 'denitrification' (Figure 2, Box 2).

In addition to N surplus serving as a proxy for potential total N losses via  $\text{NH}_3$  volatilization, N leaching and denitrification, it also reflects possible changes in the N stock of the system. It may also reflect uncertainties in the estimation of the N input and N output items of the N mass balance. In the present example for the cropping system shown in Figure 7c, we have shown a target value for maximum N surplus at 80 kg N per ha per year. As with the target NUE range and the target N output, the exact target value for any situation is a question for engagement between science, practice and policy communities, which may depend on regional and local context. For example, target values of maximum N surplus may depend on the balance of N loss pathways and the threshold values for N species concentrations in groundwater and surface water bodies, habitat vulnerability and the contribution and effects of  $\text{NH}_3$  and  $\text{N}_2\text{O}$  emissions to air.

*In summary*, reference or target values for NUE, N output and N surplus will have to depend on the type of agricultural systems and the climate-soil-environmental conditions, as well as on the type of N inputs. This means that the targets are system and location specific. The reference values presented in this chapter ( $50\% < \text{NUE} < 90\%$ ; N output  $> 80$  kg/ha/year, N surplus  $< 80$  kg/ha/year) serve as a first attempt to arrive at such reference values based on the Expert Panel's consideration of production and environmental objectives for the example of a cropping system. The target values proposed in this paper represent current average values in Europe. For example, the overall mean N output of agricultural land in EU-27 in the year 2000 was about 80 kg/ha, while the overall mean NUE of the crop production sector was 44%, and the overall mean N surplus of the EU-27 agriculture (including animal agriculture) was about 80 kg/ha (Oenema et al., 2009). In about 2010, NUE in the EU-27 had increased to more than 50% (Westhoek et al., 2014; Zhang et al., 2015)

In the next section we test these values against several examples of data at different scales, and further reflect on the target setting process in Chapter 7. Ultimately the setting of such target values combines issues of system performance and relationships (science community), achievability and food-system benefits (practice community) and management of societal risks (policy community). As such, the setting of target values in different geographic and system contexts needs to involve all three communities.

Further, the N inputs and N outputs need to be defined in relation to the system boundaries (Box 4).

#### **Box 4. Defining N inputs and N outputs in relation to system boundaries**

In developing the NUE approach it is important to be clear about which N inputs and which N outputs are included. These will differ according to (i) system boundaries, and (ii) the purpose of the user(s). In principle, many different systems and system boundaries can be considered, and these need to be defined carefully. Also, different purposes of using the NUE approach can be considered, including (a) comparing different systems, (b) monitoring progress over time, and (c) identifying the need for and effectiveness of management measures.

In the example given in Figure 7, the NUE is defined for a cropping system, which may be applied from field to regional scales. In principle, all N inputs and N outputs need to be considered, otherwise this alters the interpretation of results in relation to the setting of target values for each of NUE minimum, NUE maximum, N outputs and N surplus. At the field scale for crop NUE, this means that all N inputs via fertilizer, biological N fixation, manure and other organic residue and atmospheric deposition need to be considered. Similarly, in principle, outputs need to include all harvested and withdrawn products, including crop harvest and other products if they are removed (e.g. straw). Under certain circumstances and for certain purposes (e.g. monitoring progress over time) it may be appropriate to simplify the inputs to the manageable inputs, in order to make it easier to obtain the relevant data. A preference should, however, be given for using default values if information is not available, rather than excluding an N input term. In this way, the use of default values can stimulate users to develop values that are more representative for each system under consideration.

In the case of NUE for livestock production, a key question about the system boundaries is whether only the feed conversion efficiency is considered (livestock NUE), or whether the NUE efficiency of the feed production is also included (livestock system NUE). The distinction should also be understood between N input and N output terms and between N recycling terms. As a result, what may be considered as an N input in one system may constitute a recycling term in another system. For example, the addition of livestock manure to a field represents an input when considering crop NUE only. By contrast, when considering NUE of the livestock production system (livestock system NUE), livestock manure represents a recycling term. This means that manure is not included as an N input in this case. But this does not mean that such recycling is not important (see also section 7.6). Effective recycling of manure and other organic residues means that more N outputs can be produced with a smaller amount of new N input via fertilizers, biological N<sub>2</sub> fixation, and atmospheric deposition). In this way, livestock system NUE allows the benefits of better manure management to be recognized.

The example of atmospheric N deposition is another case which can be considered as an N input or recycling term according to the definition of system boundaries. Most atmospheric deposition of N results from emissions of nitrogen oxides (NO<sub>x</sub>) and ammonia (NH<sub>3</sub>). However, in the case of NH<sub>3</sub> in Europe, around 90% of emissions to the atmosphere derive from agricultural sources (manures, fertilizers). Conversely, over 90% of European NO<sub>x</sub> emissions result from combustion sources (energy production, transport, industry), which represents a new formation of reactive N. The N deposition resulting from both sources can provide a substantial contribution to crop growth. This means that when framing a definition of "Economy-wide NUE", the N inputs from fertilizer production, biological N fixation and NO<sub>x</sub> formation represent new N inputs, while NH<sub>3</sub> deposition represents recycling N. As with the example of manure, this does not mean NH<sub>3</sub> is forgotten. As a recycling term, better management to reduce NH<sub>3</sub> losses will contribute to both improving Economy-wide NUE and to reducing its adverse environmental effects.

These examples illustrate how particular care is needed in interpreting numerical results of NUE, according to the choice of system boundaries and the choice of which N inputs and outputs are included. In the following examples in chapters 4, 5 and 6, attention is given to explain how the choice of including or excluding certain N input and N output terms affects the interpretation.

#### 4. Illustration of the concept; case-studies using data from N fertilization trials.

##### 4.1. Long-term Broadbalk winter wheat experiment in United Kingdom

The Broadbalk experiment at Rothamsted in United Kingdom is the oldest continuous agronomic experiment in the world. It started in 1843, and winter wheat has been sown and harvested every year since then. The fertilizer treatments have been maintained annually since that time, with the control plots having no fertilizers, manure, composts or other residues added. Figure 8 shows the mean results for the period 1996 to 2012, when a single winter wheat variety (Hereward) was grown in every year. The data summarised cover the full range of current N fertilizer rates and is for (a) continuous wheat – i.e., monoculture with no crop rotation and (b) first year wheat in a rotation of oats – maize – wheat – wheat – wheat. Wheat yields (and N yields) are much better for first year wheat than for continuous wheat, because of the decreased incidence of soil-born fungal diseases in crop rotations.

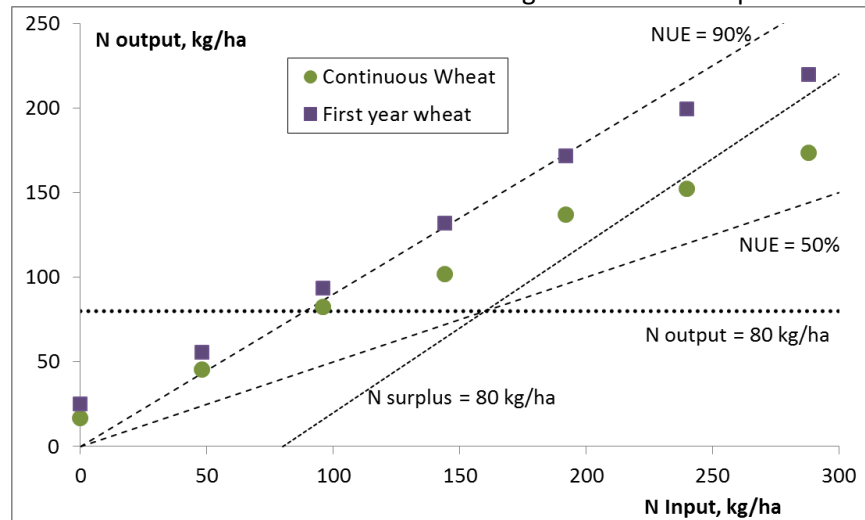


Figure 8. Relationship between annual N input via N fertilizer and annual N output via harvested grains and straw for continuous wheat and first-year wheat in a rotation of oats – maize – wheat – wheat – wheat from 1843 onwards. Mean results of the Broadbalk winter wheat experiment in Rothamsted for the period 1996-2012. The N output includes the N in grain and straw. The dotted lines indicate possible target values for NUE (50 and 90%), for N output (80 kg per ha) and N surplus (80 kg per ha) as indicated in Figure 7 (Data points from: MacDonald et al., 2015). No manure was added to the experimental treatments. Other N inputs not included here include atmospheric deposition estimated at 30 kg N /ha/yr and biological N fixation at <5 kg N/ ha/yr. The consequences of excluding these terms from the present graph are discussed in the text.

Yields responded to fertilizer N application through the full range of N inputs tested up to 280 kg/ha/year. Low N application rates (0 to 50 kg/ha) gave a slightly higher NUE than 90%, suggesting that N sources other than N fertilizer may have been utilized (i.e. from soil, and atmospheric N deposition). The mid application range (96, 144, 192 kg/ha/yr) fall within the ‘desirable NUE range’ for continuous wheat. At high N application rates (>200 kg/ha/yr) NUE values tend to decrease, but NUE is still in the ‘desirable range’. For first year wheat after a break crop, all NUE values are higher than for monoculture wheat.

It should be noted that these conclusions would be slightly altered if other N inputs are considered, while retaining the same performance targets. While no manure was added to these experimental trials and biological N fixation is estimated to be negligible small at this site ( $< 5 \text{ kg N /ha/yr}$ ), atmospheric N deposition is known to be significant (estimated at  $30 \text{ kg N/ha/yr}$ ). Hence, the actual N inputs were about  $30 \text{ kg/ha/yr}$  higher than actually shown; i.e., the dots in the figure should have been moved horizontally  $30 \text{ kg/ha}$  to the right-hand side of the figure.

It should be noted also that there is also a large scatter in the N output between years (not shown). For each N rate, and for both continuous wheat and first year wheat, there is a wide range of N output and therefore also in NUE and N surplus values between years. This reflects yield variations between years, which is largely a result of differences in weather conditions and/or disease or pest incidence. The N output ranged between years from about  $25 \text{ kg/ha}$  for the control treatment (unfertilized treatment) up to  $100 \text{ kg/ha}$  for treatments receiving more than  $100 \text{ kg/ha/year}$ , during the 16-years period (1996-2012). Hence, long-term monitoring data are very useful for establishing robust means and for assessing annual variability in NUE, N output and N surplus.

In summary, the results of the Broadbalk winter wheat experiment at Rothamsted for the period 1996-2012 (Figure 8), show the usefulness of the NUE indicator. Results indicate that the tentative reference values for NUE, N output and N surplus are achievable and realistic for 'high input - high output' winter wheat cultivation; high N inputs can go along with high N outputs and N surpluses of less than  $80 \text{ kg N/ha/yr}$  for crops like winter wheat and when well-managed. Finally, it shows the importance of crop rotations for achieving high NUE, high N output, and low N surplus simultaneously.

#### **4.2. Short-term N fertilization experiment with winter wheat and barley in Spain**

Figure 9 shows the results of a N fertilization experiment with winter wheat and barley carried out under Mediterranean conditions in Spain for two years. The N inputs via N fertilizer were taken into account, while no manure or other organic residue was added. Atmospheric N deposition was not estimated, but is expected to be less than  $30 \text{ kg N /ha/yr}$  for this situation. With low levels of fertilizer N input, NUE was much larger than 100% for the wheat trials implying a depletion of soil N stocks. With increasing fertilizer N input, NUE decreased to values in the range of 50 to 90%.

At low N fertilizer input, the N output of winter wheat was much higher in this short-term experiment than in the long-term Broadbalk winter wheat experiment discussed in Section 4.1. This can be explained by the winter wheat at the control treatment (the treatment where fertilizer N applications were withheld) in this short-term experiment having benefitted from the built-up of soil fertility in the recent past and from residual fertilizer N from previous years. By comparison, the control for the Broadbalk winter wheat experiment had not received additional N inputs for over a century, the only major source of N input being atmospheric deposition. As a result, the soil fertility level in the control treatment (and the treatment with low N application rates) of the long-term Broadbalk winter wheat experiment has been depleted over time, while the soil fertility level in the short term field experiment in Spain has been build-up, until the start of the experiment.

The winter wheat in the Spanish experiment was grown in an area and in years that received 600 to 700 mm of rain, while the barley was grown in an area and in a year with only 400 mm of rain. As a

consequence, N output of the barley was much smaller at this water-limited site. Rainfall is a very important factor in the N response of dryland crops, and greatly affects N output. The result is that water-limitation tends to decrease NUE and increase N surplus. If rainfall is below 300 mm per year, most farmers do not use N fertilizer or they wait to apply fertilizer when the first rains come. As a result, the mean N output via harvested cereals is only in the range of 40-70 kg N/year, with a fertilizer N input ranging from 0 to 100 kg/ha. Note that the N surplus is not necessarily lost in semi-arid conditions; it may be utilized by a subsequent crop if the roots are able to mop up the residual N from the subsoil. There are about 6 million ha of rain-fed winter cereals in Spain. Elsewhere in the world, there are also large areas of semi-arid agricultural land, where water limits crop growth and the utilization of N. These systems often have a low N input and large annual variation in productivity (N output).

In summary, the results of the short-term N fertilization experiments with winter wheat and barley in Spain (Figure 9) show again the applicability of the NUE indicator. Comparison of the results of this short-term experiment with those of the long-term Broadbalk winter wheat experiment reveals the importance of soil fertility build-up in the past and of residual fertilizer N for achieving a high NUE in the short term. The comparison of Wheat and Barley in Figure 9 also shows that the limited water availability reduces N output and thereby NUE. On the one hand, this highlights that lower N outputs are expected in semi-arid, dryland farming conditions and that the tentative target N output of 80 kg N/ha/yr may not always be achievable. Similar limitations may occur on poor soils or in very cold climates.

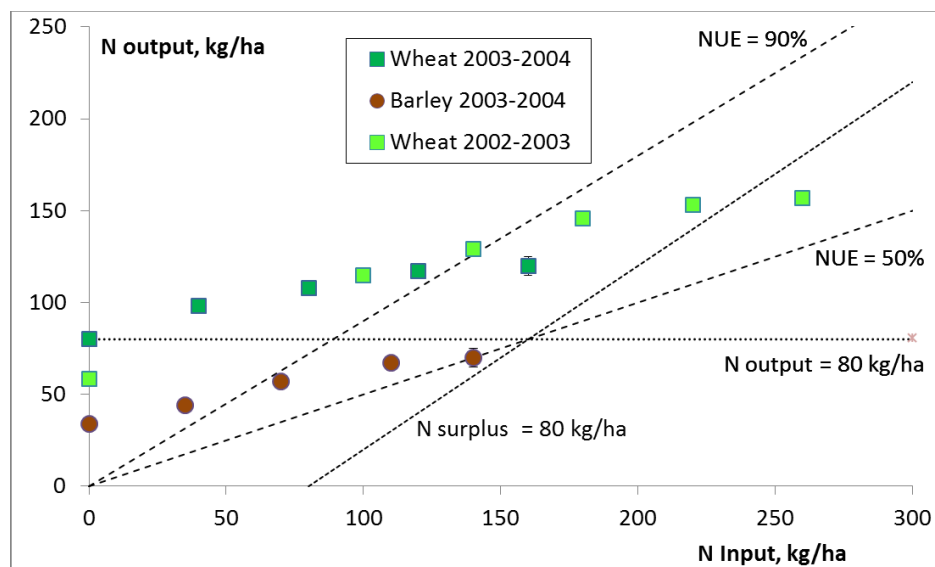


Figure 9. Relationship between N input via N fertilizer and N output via harvested grains for three N fertilization trials carried out in Spain during 2002-2004. The winter wheat was grown in a relatively moist area and barley in a relatively dry area. No manures or other organic residues were added during the experimental years, while the N input axis represents only fertilizer input. Atmospheric N deposition was not assessed. The dotted lines indicate possible target values for NUE (50 and 90%), for N output (80 kg per ha) and N surplus (80 kg per ha) as indicated in Figure 7. (Data points from Arregui et al., 2006 and Arregui and Quemada, 2008).

#### 4.3. Short-term fertigation experiment with potatoes in The Netherlands

Commonly, fertilizer N is split-applied to arable crops with 30 to 60% at the start of the growing season and the remainder in one or more dressings during the growing season. Split application tends to increase N output and NUE and thereby lowers N surplus. Fertigation, i.e., applying fertilizer N together with (drip) irrigation is a method designed to further enhance N output and NUE, because it may bring the N fertilizer and water in a directly available form in the vicinity of the plant roots. Fertigation thereby circumvents the possible drawback of split application, when the second or third application is applied during relatively dry weather conditions and the fertilizer granules remain at a dry soil surface out of the reach of the roots.

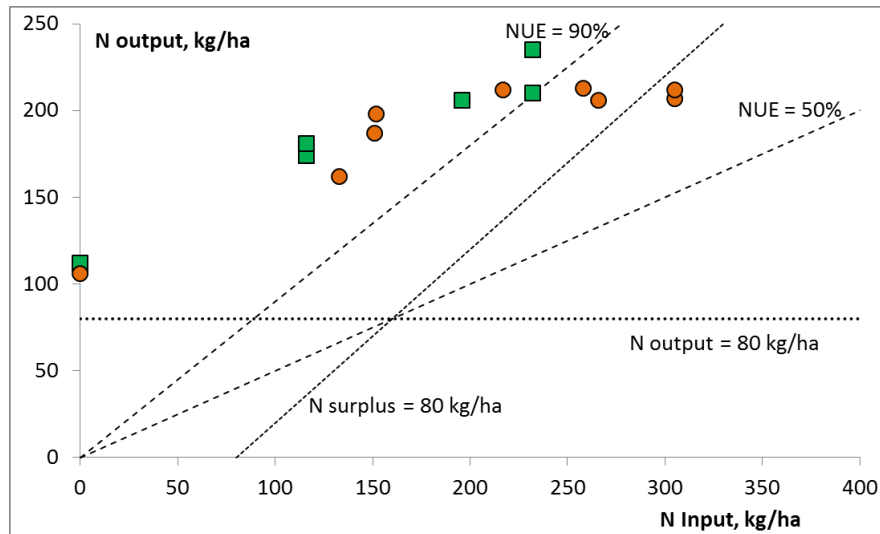


Figure 10. Relationship between N input via N fertilizer and N output via harvested potato tubers grown on a loamy soil in Lelystad in The Netherlands. Fertilizer N was split applied, with two-third at planting and one-third via fertigation during the growing season. Green dots are for 1998, orange dots for the 1999 season. No manures or other organic residues were added during the experimental years, while the N input axis shown represents only fertilizer input. Atmospheric N deposition was not assessed. The dotted lines indicate possible target values for NUE (50 and 90%), for N output (80 kg per ha) and N surplus (80 kg per ha) as indicated in Figure 7 (data points from Postma and van Erp 2000).

Figure 10 shows the results of a short-term N fertilizer experiment with potato as a test crop and with the second and third N fertilizer dressing applied via fertigation. Effects of fertigation were variable and there were no statistical significant differences in yield and N output between treatments receiving N fertilizer via fertigation and those receiving N fertilizer as calcium carbonate – ammonium nitrate granules. Lack of a clear response to fertigation is likely related to the fact that rainfall was sufficient in The Netherlands in these years, and because the experiment was carried out on a fertile marine clay soil with a high soil moisture holding capacity and a high soil N supplying capacity. The N output increased with fertilizer N application to a level of about 200 to 250 kg/ha/year. The high N output of the unfertilized control treatment is much larger than could have been supplied by atmospheric N deposition (not assessed but expected to be less than 40 kg N /ha/year). With NUE much larger than 100%, the results therefore indicate that the soil was able to provide N through the mineralization of soil

organic N. The indication of substantial soil N stock contributions suggests that it may be desirable to aim for >90% NUE in some cases as a deliberate temporary mining of soil N reserves, also to reduce the risk of N losses.

In summary, the results of the short-term fertigation experiment with potatoes (Figure 10) show that effects of fertigation on NUE, N output and N surplus can be illustrated with the NUE indicator. The same holds for other options for improving N management, such as the use of split applications and different types of N fertilizers (e.g., Mosier et al., 2004). Figure 10 also shows that high potato yields can be achieved with high NUE values. The results also suggest that NUE values of more than 90% can be justified for some time, if the mineralizable N stock is high e.g. due to previous application of manures or crop residues.

#### **4.4. Short-term N fertilization experiment with tea in Kenya**

Tea is grown as a perennial tree bush monoculture that can be in economic production for up to 100 years if well managed. This approach is especially practiced in China, India, Kenya and Japan. The cultivated tea (*Camellia sinensis* (L.) is maintained as a low bush in a continuous vegetative phase by pruning every 3-5 years to form a plucking table that facilitates removal of the young shoots. The pruned material is left on the soil which favours recycling of nutrients and organic matter, thus contributing to the nutrient and organic matter balances of the soil, and preventing erosion in young plantations (Kamau et al., 2012). Use of N fertilizers can increase productivity per unit area under good management in commercial tea plantations, with rates ranging from 100 to 300 N kg/ha/yr and more. Recommendations on fertilizer composition and rates are usually based on the ratio and amounts of nutrients removed. Fertilizer N recommendations for mature tea vary between tea growing regions, depending also on the yielding ability of genotypes.

The relationships between N fertilizer input and N output in harvested tea (two leaves and a bud) for clonal and seedling tea in a short-term N fertilization experiment in Kenya for the years 2002 and 2003 is shown in Figure 11 (Kamau et al., 2008). The four sites were located within a radius of four km from Kericho, Kenya at an elevation of 2200 m above sea level. Previously, tea bushes were managed intensively at this site with N applications in the range of 100 to 300 kg/ha/yr and other nutrients in the ratio of NPKS =25:5:5:5.

Figure 11 shows that the responses to N fertilizer applications were low during the two-years study period, with little differences between years. For trees grown from seed (43 and 76 year old trees), there was hardly any response of N output to increasing fertilizer inputs. The results suggest that the previous high level of fertilizer applications at this site and the return of pruning biomass to the soil had built-up a high level of soil N stock for the tea bushes making N fertilizer application effectively redundant during the two years of the experiment.

Figure 11 also shows results for younger clonal tea trees (14 and 29 years old), which had a slightly larger response to increasing fertilizer N inputs than the older trees grown from seed. However, the response was low, indicating that that the soil N stocks was also here a major source of utilized N.

Unfortunately, no long-term fertilization trials are available for tea. Therefore, it remains unclear for how long these sites remain ‘unresponsive’ to fertilizer N application.

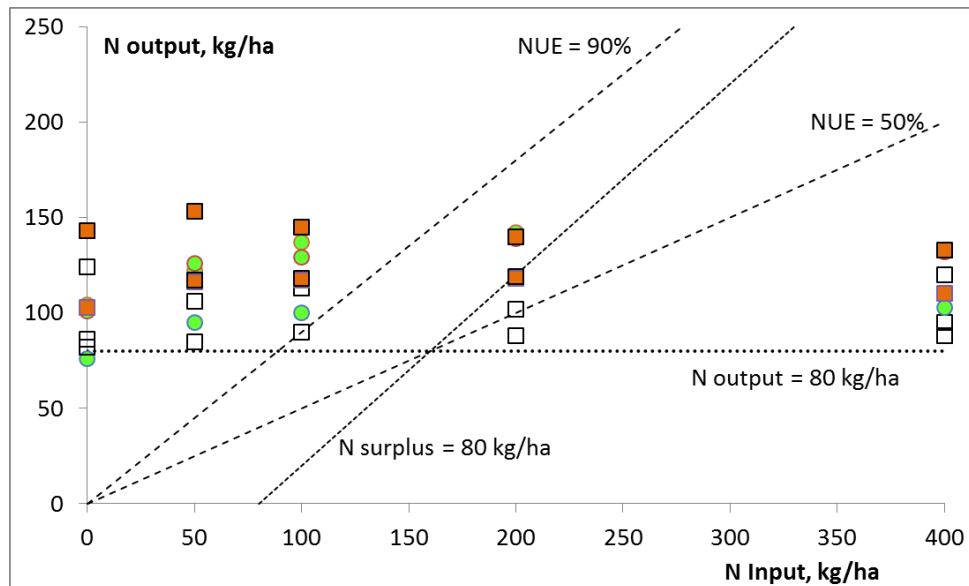


Figure 11. Relationship between N input via urea N fertilizer and N output via harvested ‘two leaves and a bud’ tea leaves in experimental fields in Kericho, Kenya. Results of two experiments with clonal trees of 14 and 29 years age (green circles) and two experiments with trees grown from seed of 43 and 76 years age (squares) for the seasons 2002-2003 (open symbols) and 2003-2004 (closed symbols). Means of triplicates. No manures or other organic residues were added during the experimental years, while the N input axis shown represents only fertilizer input. Atmospheric N deposition was not assessed. The dotted lines indicate possible target values for NUE (50 and 90%), for N output (80 kg per ha) and N surplus (80 kg per ha) as indicated in Figure 7 (Data points from Kamau et al, 2008).

In summary, the results of the short-term N fertilization experiment in tea plantations in Kenya (Figure 11) show the usefulness again of the NUE indicator. A relatively high N output and high NUE was combined with relatively low N surpluses, which was achieved by mining of available soil N stocks. It appears that the soil N stocks were high due to fertilization in previous years, which would have been facilitated by a high organic matter content resulting from returning pruning material to the soil surface. This suggests that fertilizer addition is not beneficial in this context, although it remains unclear for how long this situation may continue. The observations reiterate the importance of soil fertility level and residual fertilizer N for a proper interpretation of N input – N output relationships. The results also show that it may be desirable for management to deliberately seek to exceed the >90% NUE boundary by reducing N fertilizer inputs, for a limited period. The experiment here shows that the N outputs were in almost all cases >80 kg N/ha/yr, while N fertilizer inputs at 200 and 400 kg /ha/yr led to a N surplus >80 kg N/ha/yr. For fertilizer N inputs at 50 and 100 kg/ha/yr the N surplus was low.



## 5. Illustration of the concept; cases studies using national data statistics

### 5.1. Crop production systems at national level in EU-28 for the period 1961-2009

Lassaletta et al (2014a,b) analysed the trajectory of N inputs and N outputs in harvested produce of crop production systems in the world at country level for the period 1961 to 2009. The crop production systems within a country were defined on the basis of statistical data in the FAOSTAT database; it included all arable land (including temporary leys) and permanent crops (fruit orchards, vineyards, olive orchards), but permanent grassland was excluded. Total annual crop production and N output by each country was calculated by taking into account the annual yield of 178 crops and their N content. The cropped surface area was estimated by summing up the surface areas of all individual crops.

Figure 12 presents the relationship between N output and N input of cropping systems for four countries in Europe during the period 1960 to 2009, as examples to illustrate the case. Each dot in Figure 12 represents the estimated annual average value of the whole crop production system of a country. From 1960 to about 1990, N input and N output tended to increase, while NUE tended to decrease in this period (most clearly seen for Spain and Hungary). From about 1990 to 2009, N output tended to increase much more than N input and NUE increased, especially in France and Germany. The changes after about 1990, that are especially seen for France and Germany, reflect technical progress and/or changes in policy (reform of the Common Agricultural Policy, introduction of Agri-environmental policies). In Hungary there was a strong decrease in fertilizer use following the political/economic change in the beginning of the 1990s, and this decrease was associated initially with a decrease in N output.

In 2009, the crop production systems of about half of the Member States had a NUE value of 50% or more. None of the Member States had a NUE value of more than 90%, suggesting that the risk of soil mining was relatively small at a national scale. However, it cannot be excluded that some regions in central Europe have faced soil mining following the political/economic changes in the 1990s; note that the country average NUE values in Hungary have been high in some years.

The total N input via synthetic fertilizers, symbiotic N fixation, manure application and atmospheric deposition to cropland was estimated by Lassaletta et al (2014b). Changes in soil fertility level were not considered in the inputs, i.e. no assumptions were made about N inputs from soil N mineralization. Total N fertilizer use and total manure production in a country were corrected for the estimated amounts of N fertilizer and animal manure applied (or dropped) onto grassland using literature data, to estimate the fraction of N fertilizer and manure N that enters crop land. Evidently, there are uncertainties involved in the estimated N inputs via N fertilizer and animal manure, especially for countries with a relatively large grassland area, such as Ireland, United Kingdom, The Netherlands, which affect the estimated outcomes for NUE and N surplus.

In summary, the results of the study of Lassaletta et al (2014b) indicate the applicability of the NUE indicator for examining trends over time in NUE of crop production systems at country level. It allows the assessment of the effects of agri-environmental policies on NUE, N output and N surplus. It allows also the identification of changes in NUE, N output and N surplus due to for example changes in crop production systems, and due to technical progress. There are several uncertainties in the estimation of

the N inputs and N outputs; a main uncertainty relates to the apportionment of animal manures that contribute N input to crop land.

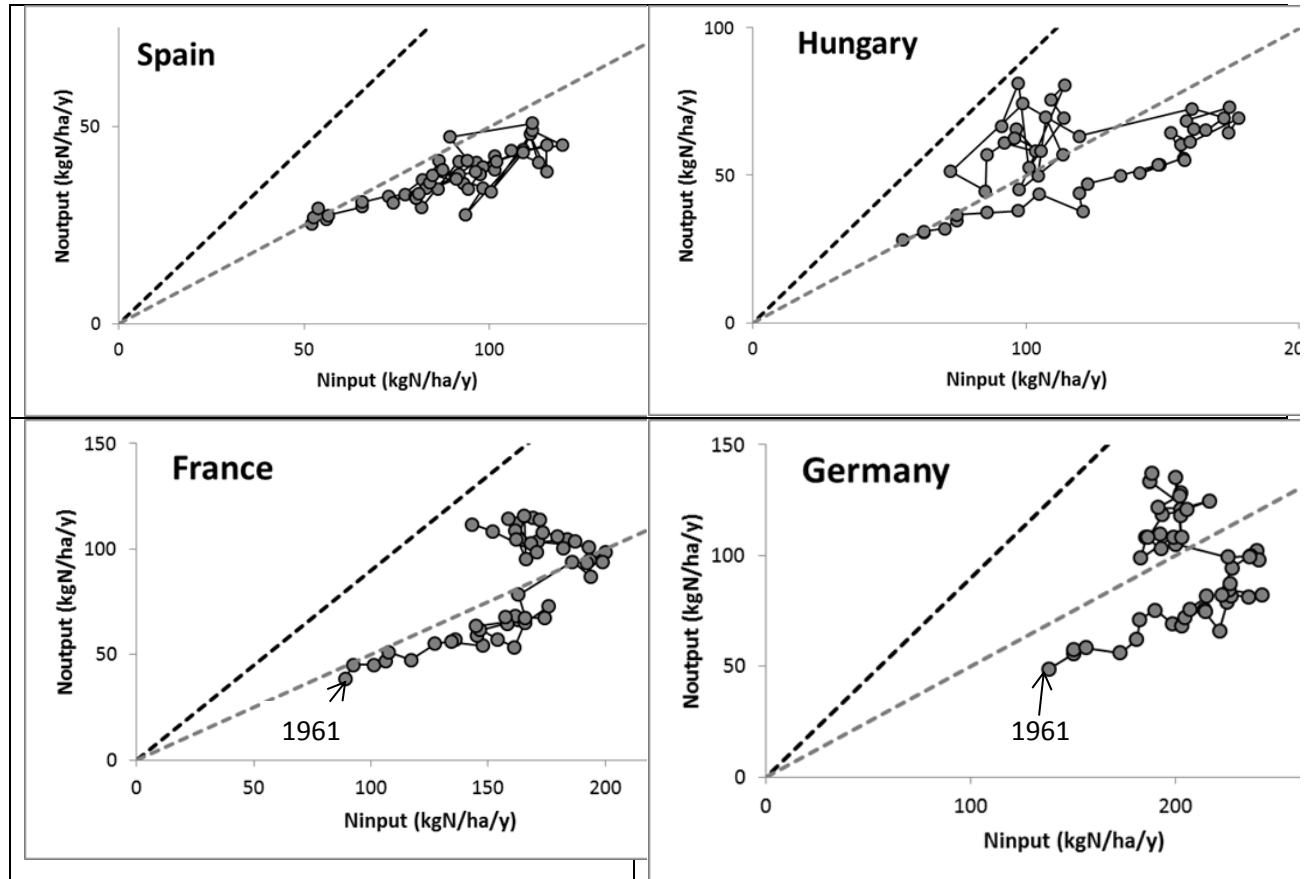


Figure 12. Examples of the relationships between N output and N input of cropping systems in four countries during the period 1961 to 2009. Each circle (grey dot) represents a the country mean for a year; lines between dots have been added to indicate how N input and N output change between years. N inputs to crops (excluding permanent grassland) included fertilizer, biological nitrogen fixation, manure and atmospheric deposition. The year 1961 is the first in the row, in the most left/bottom position. Black dotted line corresponds to a NUE of 90% and grey dotted line to a NUE of 50% NUE (data points from Lassaletta et al., 2014b).

### 5.2. Crop production systems at national level in EU-28; the Eurostat/OECD approach

Eurostat and OECD have developed and implemented the so-called ‘Gross Nitrogen Balances’ (GNB) at country level (see also Annex 2). The methodology of the GNB is described in Eurostat (2013). The GNB calculates the ‘gross nitrogen surplus’ as the difference between total inputs and total outputs of all crop production and grassland production, divided by the reference area, which is in the Eurostat database the sum of arable land (Eurostat code: L0001), permanent grassland (Eurostat code: L0002) and land under permanent crops.

Figure 13 shows the relationships between mean N inputs and mean N outputs for the 28 countries of the European Union (EU-28) for the period 2004 to 2011. Mean N inputs ranged from 60 to 370 kg/ha/yr and N output from 40 to 190 kg/ha/yr. NUE ranged from 48 to 112%; the latter value (for Romania) indicates that N output was larger than N input and suggests that soil mining was taking place. Relatively low NUE values occurred at both low and at high N inputs. Relatively high NUE values occurred only at relatively low N input. Mean N inputs and N outputs were lower for the 12 new Member States than the 15 'old' Member States (Figure 13). The 7 countries with a N surplus of more than 80 kg/ha/yr also had a N output larger than 80 kg/ha/yr. Approximately half of the countries had a N output larger than 80 kg/ha/yr. Total N inputs in EU-15 slightly decreased and that in EU-12 slightly increased during the period 2004-2011.

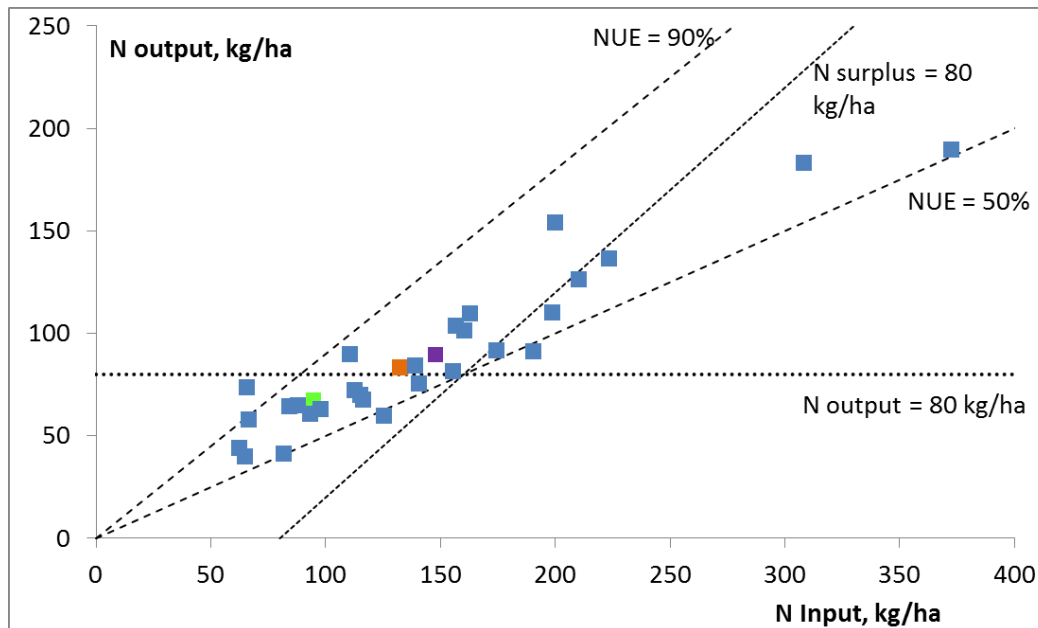


Figure 13. Relationships between N output and N input of agriculture in the Member States of the European Union (Each point represents a Member State). Eight-year means for the period 2004-2011. The green dot presents the mean for the 12 new Member States (EU-12), the orange dot the mean for EU28, and the purple dot the mean for the 15 so-called old member states (EU-15). Data source: <http://appsso.eurostat.ec.europa.eu/nui/show.do> (Data extracted 12-10-2015). Total nitrogen inputs were estimated from the N input via mineral fertilisers, composts, excreta from domestic animals, seeds and planting material, biological N<sub>2</sub> fixation, and atmospheric deposition. Total outputs were estimated from the removal of nitrogen via the harvest of arable crops, vegetables, fruits and grassland (including any crop residues removed from the field).

In summary, the data of the Gross Nitrogen Balance (GNB) of EUROSTAT/OECD can be plotted also in the two-dimensional input – output diagram of the NUE indicator. Eight-year means (period 2004-2011) were used. The GNB was estimated at national level by EUROSTAT, and the system analyzed included the agricultural sector of each country as defined in the Farm Structure Survey. The results show substantial differences between countries. Most results were in between the two NUE references values of 50 and 90%. The N surplus was always less than 80 kg/ha/year when N output was less than 80 kg/ha/yr. There were significant differences between the old and new Member States; soil N mining was

likely taken place in some of the new Member States. There are several uncertainties in the estimation of the N inputs and N outputs; the main uncertainties related to the N output was the N output via harvested grass, both via grazing and mowing (Eurostat, 2013).

## 6. Illustration of the concept; mixed crop-livestock farming systems

The examples presented in Chapters 4 and 5 indicate that the NUE concept presented in this report is applicable to various crop production systems. The concept is equally applicable to crop rotations and double or triple crop production systems, where the N input – N output relationships are either presented for each specific crop type or for a whole crop rotation or cropping system.

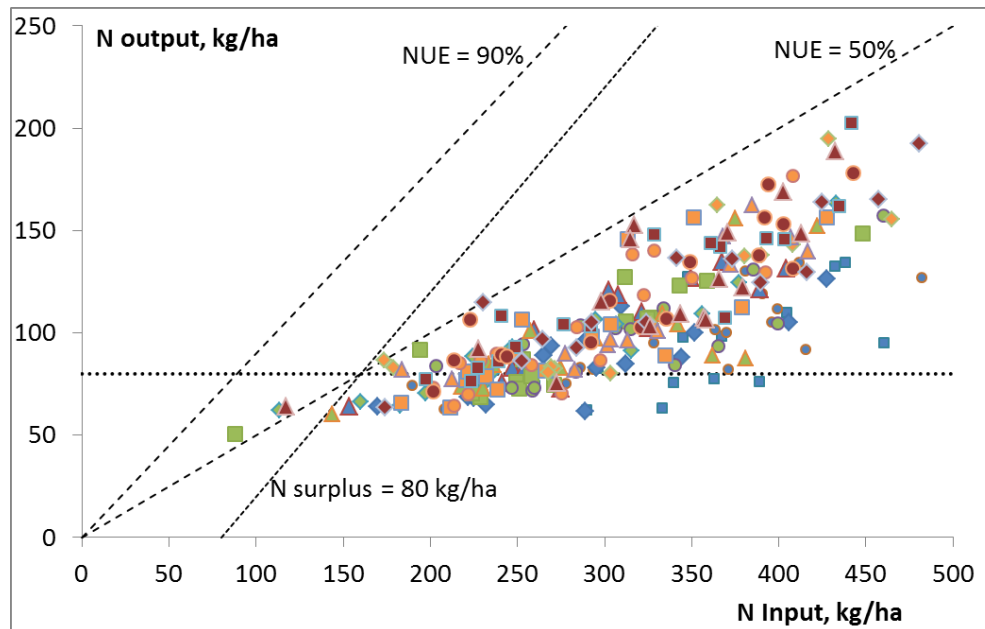


Figure 14. Relationship between total N input via N fertilizer, purchased animal feed, biological  $N_2$  fixation by clover, and atmospheric N deposition, and total N output via sales of milk and cattle on 16 specialized dairy farms in The Netherlands. Different symbols indicate different years; blue symbols 1998-2001; green symbols 2001-2005; orange symbols 2006-2009; and purple-brown symbols 2010-2013. The dotted lines indicate possible target values for NUE (50 and 90%), for N output (80 kg per ha) and N surplus (80 kg per ha) as indicated in Figure 6 (after Oenema, 2013).

The NUE concept is also applicable to mixed crop-livestock production systems, where the livestock consumes a fraction or all of the farm-grown crops, and livestock products are a significant N output of the farm. Figure 14 shows the relationships between total N input and total N output via sales of milk and cattle for 16 grassland-based dairy farms in The Netherlands during the period 1998-2013. The farms were situated on different soils (sand, clay, peat) and were researcher-guided to improve the management of the farm. The mean intensity of milk production was high (17,000 kg milk per ha per year), but ranged between farms from 10,000 to 30,000 kg/ha/year. Livestock density ranged from 2 to 5 livestock units per ha. Over time, production intensity slightly increased (not shown), concomitant with a slight increase in N output and NUE (Figure 14).

Total N input ranged from 80 to 450 kg per ha per yr, and total N output from 50 to 200 kg per ha per yr (Figure 14). NUE values ranged from 20 to 50%, and tended to increase over time. The N surplus ranged

from 50 to 300 kg per ha per year. Evidently, the suggested target values for NUE (50 to 90%), N output (>80 kg/ha/year), and N surplus (<80 kg/ha/year) are not generally achieved. This is mainly because of the relatively low efficiency of the conversion of crop protein-N in milk and meat protein-N, and the relatively high N losses via ammonia volatilization, N leaching (from urine patches) and denitrification. Over time, NUE has increased from a mean of 28% during 1998-2001 to 38% during the period 2010-2013. This increase in NUE has been the result of measures aimed to increase the productivity, to decrease N losses via  $\text{NH}_3$  volatilization and nitrate leaching, and to decrease N inputs via fertilizers and animal feed (Oenema, 2013).

In summary, the two-dimensional input – output diagram of the NUE indicator is applicable to mixed crop-livestock production systems. Monitoring of the N inputs and N outputs at farm level allows to monitor changes in NUE of the whole farming system over time. These changes may result from changes in the NUE of crop production and from changes in the NUE of animal production. Data and information at whole farming systems do not allow to make a distinction between these two components; that requires additional data. Also, mixed crop-livestock production systems may require different target values.

## 7. Discussion

### **7.1 Nitrogen use efficiency and sustainable intensification of food production**

The word and notion of 'efficiency' have recently been debated, especially in relation to 'achieving more sustainable food systems' (Garnett et al., 2015). It was argued that 'the word efficiency has become intellectually, morally and aesthetically overloaded'. The background of this notion is that different people assign different meanings to efficiency; 'some use it as a short-hand for sustainability without really thinking about it', 'others simply reject its utility as a measure of sustainability *per se*'.

Efficient food systems are not by definition sustainable food systems (Garnett et al., 2015). Efficiency is commonly defined as a ratio of output over input, while sustainability is commonly defined in much broader definitions (SDSN, 2015). In framing the present discussion around N use efficiency, we do not claim that 'high N use efficiency is equivalent to sustainable N use'. Our notion is that N is essential for life, but excess N is a threat to the environment and potentially also to our health. Our ambition therefore is to develop tools and concepts that help to increase N use efficiency in agriculture and food systems. We argue that the two-dimensional input – output diagram of the NUE indicator presented here represents a useful way to illustrate, report and monitor improvements in NUE performances within food systems.

There are also many different notions related to the concept of 'sustainable intensification' (Garnett et al., 2013; SDSN, 2013). One of the key elements in this concept is commonly perceived as 'more crop per drop and bag', i.e., more output with less input. We argue that improving NUE has the potential to contribute to sustainable intensification.

Four main directions of change in N use efficiency may be distinguished in the two-dimensional input – output diagram. The directions toward optimization depend on the starting point and may include (see Figure 15):

- (i) intensification,
- (ii) extensification,
- (iii) increasing efficiency and
- (iv) avoiding soil degradation.

Figures 12 and 14 suggest that increases in NUE in European farms are already happening in some countries and on some farms. These patterns are similar to what is known as the environmental Kuznets curve, i.e., pollution first increases and then decreases with economic growth (Zhang et al., 2015).

The NUE indicator usefully integrates the performances of food production systems related to N yield, N use efficiency and potential N losses. Nitrogen connects with many different agri-environmental indicators (Table 1, Box 3), and provides a framing that is useful to connect with other indicators such as food consumption and human health. The NUE indicator may be helpful in identifying the direction of changes in N use in food systems, particularly also at national or sectorial scale, which is critical for policy setting.

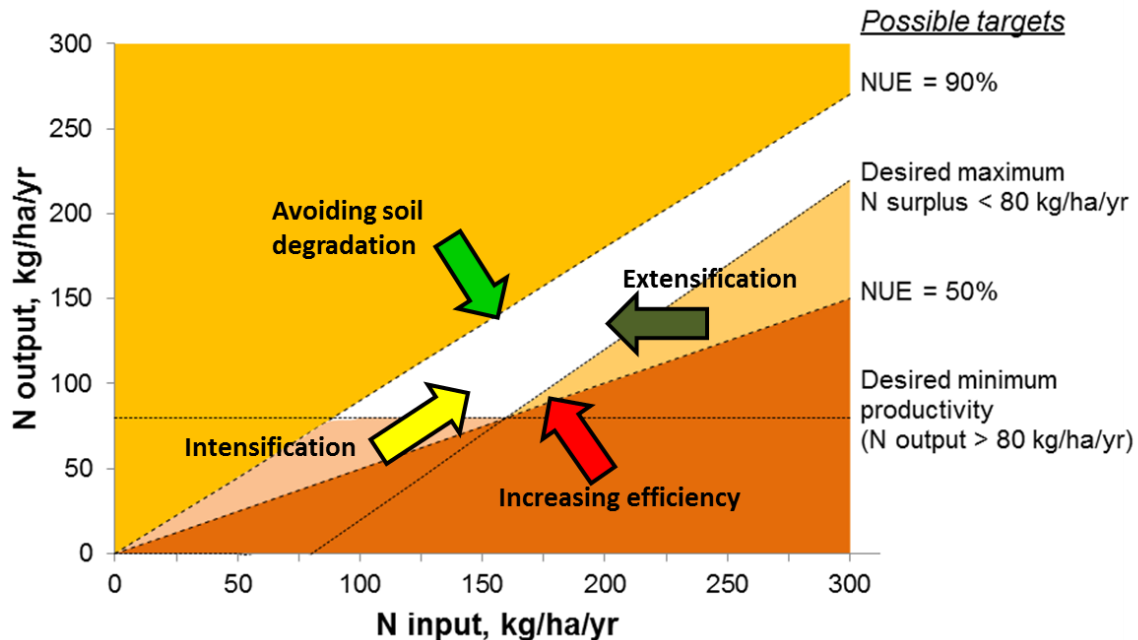


Figure 15. The Nitrogen Use Efficiency (NUE) indicator showing how different strategies can contribute toward improving N use efficiency, depending on the starting situation. According to context, both intensification and extensification strategies may contribute. In some contexts the main drive may be to increase food production and resource use efficiency, in other contexts the priority maybe to protect soil and habitats from degradation or to increase opportunities for bioenergy production and carbon sequestration.

### 7.2. A uniform NUE indicator for all food systems

The NUE indicator can be applied to all types of food production – consumption systems, although the focus in this report has been on food production. The NUE indicator is applicable at different scales, from field experiments to farms, countries and continents. It can also be used to monitor changes over time in N inputs, N outputs, NUE and N surpluses in a coherent manner. Hence, it provides a uniform framework for analyzing relationships between (and changes over time in) N inputs, N outputs, NUE and N surpluses of food production – consumption systems.

A graphical presentation of the two-dimensional input – output diagram provides direct insight into ‘the distance’ between the observed values and possible target values. Chapter 3 introduces possible target values for NUE, N output and N surplus of cropping systems, which are subjected to a series of ‘tests’ in relation to available datasets in Chapters 4, 5 and 6. For the case studies presented in Chapter 4, the proposed target values are reasonable as a first estimate. Clearly, the target value for N output (>80 kg/ha/yr) is easily met by winter wheat and potatoes grown in Western Europe, but is not so easily met in the Mediterranean during dry years. Also, the data show that target values for NUE (50 to 90%) and for N surplus (<80 kg/ha/yr) can be met when N input is not ‘too high’. No attempts have been made in Chapter 4 to estimate the economical optimal N input for the various field trials, but visual observation



of the two-dimensional diagram reveals that the marginal returns of additional N input is also rather low when the N surplus approaches 80 kg/ha/yr.

The suggested target values for NUE, N output and N surplus (Chapter 3) are not equally achievable for all crop production systems. Cereals and root crops have a relatively high N output and NUE, but many fruits have a relatively low N output. For example, olive orchards cover some 10 million ha of land in the Mediterranean and these systems have an average N output of <20 kg/ha/yr, with little fertilizer N input. Vineyards also cover millions of ha of land in EU and commonly have an N output of < 70 kg/ha/yr (Ruiz-Ramos et al., 2011). The same holds for some vegetables such as asparagus (*Asparagus officinalis* L.) with an N output in the range of only 10 to 40 kg/ha/yr (Ledgard et al 1992). Hence, when the study is related to specific cropping systems, target values must be crop-type specific.

The suggested target values for NUE, N output and N surplus (Chapter 3) reasonably apply to the broadly defined crop production systems at national level in Chapters 5.1 and 5.2. Results presented in Figure 12 clearly show that the mean N output, NUE and N surplus of crop production systems at national level have moved during the last couple of decades into the direction of >80 kg/ha/yr N output, >50% NUE, and <80 kg/ha/yr N surplus, respectively. Figure 13 indicates that there are large differences between the means of countries, especially in N output, which are related to the main crop types within a country, but also to climatic conditions. Potential crop yields are higher in western Europe than in Mediterranean, mainly because of differences in rainfall and day-time and night-time temperatures (Boogaard et al., 2013). Hence, when a study is related to cropping systems at national levels, reference values for crop production systems may have to be climate zone specific.

The two-dimensional input – output diagram is also applicable to mixed crop-livestock production systems, but target values for NUE, N output and N surplus will have to be made system specific (Chapter 6). There are more opportunities for N loss when combining crop and animal production. For a proper understanding of the observed values of such mixed crop-livestock production systems, a distinction also has to be made between the N input, N output, NUE, and N surplus of the crop production and of the livestock production components, because changes over time at farm level or differences between farms may result from changes and differences in the crop and/or livestock components (Oenema, 2013). Figure 14 illustrates that the two-dimensional input – output diagram can be used to visualize differences between farms, as well as changes over time in farm performance (e.g., as a result of technical progress).

### **7.3. Further development of target values**

The initial target values for N output, NUE and N surplus proposed in Chapter 3 are based on expert judgement considering that there is a minimum crop yield, minimum and maximum NUE and a maximum N surplus for meeting future food, feed and fibre needs in an environmentally sound way.

One way of estimating future global needs for N outputs is through normative back calculations; i.e., a human needs at least 18 kg of protein per year, which translates to 3 kg of N per capita per yr and to a minimum N output of 21 Tg per year to feed the global human population. Similar estimations can be made for the animal populations (i.e., cattle, pigs, poultry, horses, etc.). This raises questions about

norms, values and about estimates for inefficiencies in the systems, food choices, food wastes, and about the applicability of such values across the world.

Another way of estimating target values for N outputs is based on average values and/or possible values in good practice situations. For example, the overall mean N output of agricultural land in EU-27 in the year 2000 was about 80 kg/ha, while the overall mean NUE of the crop production sector was 44%, and the overall mean N surplus was about 80 kg/ha (Oenema et., 2009). That study found that through the implementation of packages of technical measures, NUE could be improved to 55% and with N losses (i.e., N surplus) reduced by 30 to 40%. There are also considerable yield gaps between current crop yields and attainable crop yields, suggesting that crop yields can be increased (Boogaart et al., 2013; Mueller et al., 2012). Several farm studies and explorative studies indicate that N surplus can be decreased while NUE is simultaneously increased.

For NUE, the initial estimate of the lower target value (50%) is roughly equivalent to the current EU mean, while there is an upper target value (here set at 90%), above which there is increasing risk of soil N mining, which is ‘unsustainable’ in the long-term. Brentrup and Pallière (2010) have developed a ‘traffic light’ indicator scheme for NUE, based on the results of a long-term field trial with winter wheat. The traffic light scheme aims to facilitate communication of possible target values to farm practice communities. It follows that, at relatively low N application rates, N removal with the harvested wheat grain tends to exceed the N input, i.e. NUE is higher than 100% (see Figures 8, 9, 10, 11). This situation is often referred to as ‘soil N mining’, i.e., depletion of soil fertility. At intermediate N application rates in the N fertilization trials of Chapter 4, the withdrawal with the wheat harvest is often similar to the N application. At high N application rates, the withdrawal with harvested wheat is much less than the N input, which indicates an increased risk of N losses.

Interpretation	Nitrogen Use Efficiency (NUE) (%)		
	Cropping systems	Mixed crop-livestock systems, 1 LSU/ha	Mixed crop-livestock systems, 2 LSU/ha
Soil N mining	>100	>80	>60
Risk of soil N mining	90-100	60-80	50-60
Balanced N fertilization	70-90	40-60	30-50
Risk of N losses	50-70	30-40	20-30
High risk of N losses	<50	<30	<20

Figure 16: A simple scheme for the interpretation of NUE values of crop production systems and mixed crop-livestock production systems (After Brentrup & Palliere, 2010). Proposed target values are tentative. LSU is Livestock Unit (equivalent to a 500 kg dairy cow).

In Figure 16, the original traffic light scheme for NUE as presented by Brentrup and Palliere (2010) has been extended. For cropping systems, the NUE values proposed by Brentrup and Palliere (2010) are shown. For mixed crop-livestock systems, lower NUE values have been proposed. These lower values reflect the fact that a longer N nutrient pathway results in larger N losses from mixed crop-livestock systems than from just crop systems (see Figures 3, 12). Livestock retains only a fraction (roughly 20 to 40%) of the protein N in animal feed in meat, milk and egg, and excrete the remainder in dung and urine. The N in dung and urine (manure) is reused again to fertilize crops, but the organically bound N in manure has to be mineralized first for becoming available to crops. Also, the mineral N in manure is vulnerable to N losses via NH<sub>3</sub> volatilization, especially during manure storage and directly following surface application to land. The N in dung and urine droppings in pastures is vulnerable to leaching and denitrification.

Zhang et al. (2015) made a global analysis of NUE of different cropping systems and continents, using the FAO database and additional calculations. The global mean NUE in 2010 was 42%. The mean NUE in Europe in 2010 was 52%. They did include atmospheric N deposition, biological N fixation and manure inputs. They also estimated a possible target NUE for 2050, using FAO projections for food demand and the allowable N pollution estimated in the planetary boundary calculations for N (Bodirsky et al 2014; Steffen et al., 2015). They arrived at a global target NUE of 67% and a target NUE for Europe of 75%. These values are in the range of values presented for cropping systems in Figure 14. However, the global analysis of Zhang et al (2015) includes all cropping systems, including mixed crop-livestock production systems, which use manure N.

Interpretation	Nitrogen surplus (kg/ha/yr)		
	Cropping systems	Mixed crop-livestock systems, 1 LSU/ha	Mixed crop-livestock systems, 2 LSU/ha
Very high	>120	>160	>200
High	80-120	120-160	160-200
Modest	50-80	90-120	130-160
Low	20-50	60-90	100-130
Very low	<20	<60	<100

Figure 17 Tentative scheme for the interpretation of N surplus values of crop production systems and mixed crop-livestock production systems with 1 and 2 livestock units (LSU) per ha. Proposed target values are tentative.

A traffic light scheme is also possible for N surplus. Figure 17 presents possible target values for N surplus of cropping systems and mixed crop-livestock production systems. Values are tentative and need further calibration and validation. On a field and farm scale, it is apparent that achievable target values will depend on climate, soil type and management options. Climate-specific and region-specific

adjustments will have to be made, because climate (rainfall patterns) greatly influence the risk and pathways of N losses, while water bodies and natural vegetation greatly differ between regions in vulnerability to N losses. The N loss pathways may also differ between regions, e.g., in organic matter rich, clayey soils a relatively large proportion of the N surplus may be lost via denitrification, while leaching is generally the dominant N loss pathway in low-organic matter, sandy soils. In sloping areas, a significant fraction of the N surplus may be lost via overland flow, erosion, surface runoff and subsurface leaching.

N surplus is related to NUE and vice versa. In formulae:

$$\text{NUE} = \text{N output} / (\text{N surplus} + \text{N output}) \quad [1]$$

$$\text{N surplus} = \text{N input} * (1 - \text{NUE}) \quad [2]$$

Formula [2] indicates that a low N surplus can be achieved through a low N input and/or a high NUE. A high N surplus is the result of a high N input and/or a low NUE. A very low N surplus is attractive from the point of view of a clean environment and a high resource use efficiency, although there is a risk that a very low N surplus is associated with soil N mining. Very low N surpluses in mixed crop-livestock production systems may be associated with overgrazing. A high N surplus is unwanted, because of the high risk of N losses and the low resource use efficiency.

Mixed crop-livestock production systems will have different target values than crop production systems, because of the increased risks of N losses from animal manures and the (s)low availability of organically bound N to crops. Two classes for livestock density have been distinguished (1 and 2 Livestock units (LSU) per ha). It has been assumed that 'attainable' N surpluses increase on average by 40 kg per LSU, based on the fact that N excretion per LSU is in the range of 100 -140 kg/LSU, and that 'unavoidable' NH<sub>3</sub> volatilization losses are in the range of 10-20 kg/LSU, leaching and denitrification losses in dung and urine between 10 and 20 kg/LSU, while 10-20 kg of organically bound N in the excreted animal manure accumulates in the soil organic matter pool and becomes available to the crop only in the course of many years in a not well-synchronized manner to crop demand.

It is tempting to present also a traffic light scheme for N output. In Chapter 3 a general target yield of 80 kg/ha/yr has been proposed. A refined traffic light scheme would necessitate a bewildering detailed scheme, as there are more than 100 different food and feed crops. N output of these crops may differ from <20 kg/ha/yr for olives to more than 400 kg/ha/yr for intensively managed forages. Instead, one mean reference value has been proposed, which is roughly the EU average.

#### **7.4. Role of soil N supply**

Soil is a major reservoir and buffer of N. Most of the N is in the organic matter and becomes available to crops following mineralization of the organically bound N to mineral N. The supply of soil N can be quantified via the harvested biomass in plots where N fertilization is withheld (unfertilized plots), although part of the N taken up from unfertilized plots may originate from atmospheric deposition and biological N<sub>2</sub> fixation.

In practice, a relatively large fraction of the N output originates from soil N supply. This fraction ranges from 25 kg/ha/yr in plots where N fertilization was withheld for more than 150 years (Figure 8) to 100

kg/ha/yr and more in plots that have received regular N input in the recent past (Figures 9, 10, 11). Evidently, this soil N supply is not for free; it has to be maintained or built-up through input of crop residues, manure and/or compost. If not, the soil N supply decreases, as in the unfertilized lots of the Broadbalk wheat experiment in Rothamsted (Figure 8). Excessive N inputs in the recent past may lead to situations where crops become 'unresponsive' to N application for at least two years (Figure 11), in part through uptake of residual mineral N from the subsoil, in part through mineralization of easily degradable organic N.

Soil N mining is beneficial in the case of mopping up residual mineral N and mineral N released from the mineralization of easily degradable organic N. In that case, soil mining minimizes the risk of N losses through N leaching and denitrification. Cover crops or catch crops grown after a main crop serve precisely that function. Soil N mining becomes deleterious when the soil N supply decreases to the levels observed in the unfertilized plots of the Broadbalk wheat experiment in Rothamsted. In this case, soil organic N content and soil fertility have decreased to a level where soil degradation is looming. In the ideal case, soil N supply is larger than about 50 kg/ha/yr and less than about 150 kg/ha/yr. Soil N mining may also occur when the input of (organically bound) N is limited, soil cultivation relatively intensive, and under conditions of climate change. This indicates that monitoring of the soil N content is important.

#### **7.5. Suggested use of the NUE indicator**

The NUE indicator presented in this report is easily applicable to different food production (and consumption) systems, and to a range of scales. The indicator is especially useful for monitoring changes at farm level and national level, to detect the effects of technical progress and policy interventions. The indicator can be used by breeding companies and the fertilizer industry to compare the NUE of different breeds and fertilizer types and N management strategies, respectively. Advisory services and accountancy offices may use the indicator in extension work to farmers. Ideally, the NUE indicator would also be used by farmers to examine the performance of the farm management. The flexibility of the indicator allows diverse applications.

Nitrogen use efficiency impacts many of the recently approved Sustainable Development Goals (SDGs) for the post-2015 era, for which concrete targets, pathways and indicators need to be developed at country scale and below. The proposed NUE indicator is suitable for setting realistic targets and monitoring of progress in that context, particularly in relation to SDG 2 (Food and nutrition security), SDG 12 (Sustainable consumption and production), SDG 14 (Marine ecosystems) and SDG 15 (Terrestrial ecosystems).

Eurostat, OECD, EEA and JRC all prepare overviews of N use and losses at regional and national levels in the EU-28. The emphasis in these studies is on fertilizer N use, the Gross Nitrogen Balance (GNB) and N budgets and losses (Table 1). We recommend that NUE indicator is included in these overviews, to monitor the changes in N use efficiency of food production (and consumption) systems over time.

Within the Farm Accountancy Data Network (FADN) data and information are collected on a representative set of farms across EU-28. These data can be used also to estimate NUE by using the NUE indicator presented here. The FADN data allow relationships between economic indicators and N use and NUE to be quantified. The Farm Structure Survey (FFS) and the FADN use structured formats for

collecting data in a uniform way at farm level across all Member States in EU-28, which allows estimates of N input, N output, NUE and N surplus at aggregated levels (farm types, regions, countries) to be calculated.

*In summary*, the NUE indicator is meant for farmers, extension services, industry, policy officers and researchers.

**7.6. Need for protocols for uniform data and information collection, processing and reporting**

The NUE indicator requires accurate N input and N output data of well-defined systems. These data and information have to be collected, processed and reported in a uniform way, to allow comparison between systems and between years, and to relate observed values to possible reference (or benchmark) values. This uniformity is needed when different agencies and offices are involved in data and information collection, processing and reporting, and when cross comparisons are made between countries or between systems. In the end, it has to be assured that any differences between systems or between countries originate from differences between the systems or between countries, and not from differences in data and information collection, processing and reporting.

Ideally, all N inputs and N outputs of a system are recorded over a one year period. Table 2 presents the input and output items used for estimating the Gross N Balance (GNB) at regional and national levels in EU-28. These data allow N output, NUE and N surplus of the NUE indicator to be estimated. Livestock manure represents the amount of N in the excreta of all farm animals, as observed in the FSS database. The amount of N in the excreta is not corrected for N losses during storage. The N input items thus represent the potential amount that enters agricultural land (hence, gross N balance). This means that losses of N during animal housing and storage appear implicitly in the GNB approach as part of the losses at the field scale.

*Table 2: Input and output items considered for the calculation of the gross N balance of crop production at regional or national levels, according to Eurostat (2013).*

Nitrogen input items	Nitrogen output items
Mineral fertilizers	Harvested arable and permanent crops
Livestock manure	Harvested fodder crops and pasture
Biological nitrogen fixation	Residues removed
Atmospheric deposition	
Compost and sewage sludge	
Seed and planting material	

In addition to the gross N balance (which represents a ‘soil surface balance’ approach for cropping systems), a ‘farm-gate nitrogen balance’ can be derived. In this case, all N input items that enter the system and all N output items that ultimately leave the system as marketed outputs (crop and animal derived products) are considered. Internal N flows and cycling, e.g. feed production and manure use within a farm, country or region are neglected, unless the feed or manure are imported or exported from the system. This approach is similar to what is called the ‘farm-gate balance’ or the ‘farm budget’ approach (Eurostat, 2013; OECD, 2015). Table 3 presents the input and output items used for estimating the ‘farm-gate balance’.

Input and output items have to be reported only once on the balance. In the case that animals are imported to the farm and other animals are exported, only the net results should be presented, i.e., on the right-hand side of the balance. Similarly, in the case that animal manure is imported to the farm and other manure exported, only the net manure input should be reported (Table 3). Reporting the inputs and outputs on the proper side of the balance allows a better comparison between farms and between countries.

*Table 3. Input and output items considered for the farm gate balance at regional and national levels, according to Eurostat, 2013; OECD (2015)*

<b>Nitrogen input items</b>	<b>Nitrogen output items</b>
Mineral fertilizers	Marketed arable and permanent crops
Imported feed (net)	Exported animals (net)
Biological nitrogen fixation	Marketed animals milk, meat, egg
Atmospheric deposition	
Compost and sewage sludge	
Seed and planting material	
Imported animal manure (net)	

In specific cases, such as the N fertilization trials discussed in Chapter 4, other N input items such as atmospheric N deposition, biological N<sub>2</sub> fixation, and imported seeds are often neglected. In such studies, the change in N output is seen as a response of N fertilizer input (or manure N input if treatments include manures), especially when N output of fertilized treatments are corrected for the N output of the control treatment. In the latter case, possible effects of atmospheric N deposition, biological N fixation, and imported seeds are implicitly addressed via the N output of the control treatment where fertilizer N was withheld. For some purposes (e.g. crop performance trials) this simple approach suffices to use the NUE indicator, as long as the system and the N input items are clearly described. However, it may not be sufficient for all purposes, especially when looking to optimize systems for dual production and environmental performances.

The simplified approach of only including fertilizer (and manure) N inputs that is often used in crop-trials does not hold when the objective is to compare different farms, different cropping systems and/or different countries. In this case, all N input and N output items listed in Table 2 or Table 3 have to be recorded, because N inputs via atmospheric N deposition and biological N<sub>2</sub> fixation may differ greatly between systems.

### **7.7. Future work**

This report is the first in a series of reports dealing with the NUE indicator of the EU Nitrogen Expert Panel. This report describes the general concept and illustrates the applicability to different systems. Follow-up reports are foreseen for applications at (i) arable farms, (ii) food production – consumption systems at national level, and (iii) mixed crop-livestock farms. The purpose of these follow-up reports is (a) to further develop and apply the NUE indicator, (b) to analyze the indicated systems with the NUE indicator, and (iii) to provide formats and guidelines to users of the NUE indicator. In parallel, it is expected that further discussion of the NUE indicator through these reports can contribute to

developing better understanding as a basis for refining consensus on suitable N target values for different practice and policy purposes.



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**Annex 1. Nitrogen use efficiency indicators in crop production, with indicative target levels for cereals (after Doberman, 2007).**

Index	Calculation <sup>3)</sup>	Interpretation	Target levels for cereals
<b>RE</b> = apparent recovery efficiency of applied nitrogen (kg N taken up by the crop per kg of applied nitrogen)	$RE = (U_N - U_0) / F_N$	<ul style="list-style-type: none"> <li>RE depends on the congruence between plant demand for N and the release of N from fertilizer.</li> <li>RE is affected by the application method (amount, timing, placement, N form) and factors that determine the size of the crop nitrogen sink (genotype)</li> </ul>	0.5 – 0.7 kg/kg;  0.7 – 0.9 kg/kg in well-managed systems at low levels of N use.
<b>PE</b> = Physiological efficiency of applied nitrogen (kg yield increase per kg increase in N uptake from applied nitrogen)	$PE = (Y_N - Y_0) / (U_N - U_0)$	<ul style="list-style-type: none"> <li>Ability of a plant to transform N acquired from fertilizer into economic yield</li> <li>Depends on crop genotype (C4&gt;C3 crops, harvest index) environment and management</li> <li>Very low PE suggests unbalanced fertilization: excessive N applications or deficiency of other nutrients or mineral toxicity.</li> <li>High PE suggests high internal N use efficiency..</li> </ul>	40 – 60 kg/kg;  > 50 kg/kg in well-managed systems, at low levels of N use.
<b>IE</b> = Internal utilization efficiency of nitrogen (kg yield per kg N uptake)	$IE = Y / U_N$	<ul style="list-style-type: none"> <li>Ability of a plant to transform N acquired from all N sources into economic yield</li> <li>Depends on genotype, environment and management</li> <li>Very high IE suggests N deficiency</li> <li>Low IE suggests poor internal N conversion due to other stresses (nutrient deficiencies, drought stress, heat stress, mineral toxicity, pests).</li> </ul>	40 – 60 kg/kg;  > 50 kg/kg in well-managed systems, at low levels of N use.
<b>AE</b> = Agronomic efficiency of applied nitrogen (kg yield increase per kg N applied)	$AE = (Y_N - Y_0) / F$ or $AE = RE * PE$	<ul style="list-style-type: none"> <li>Product of N recovery from fertilizer (RE) and the efficiency with which the plant uses each additional unit of N (PE)</li> <li>Depends on management practices that affect RE and PE</li> </ul>	10 – 30 kg/kg; > 25 kg/kg in well-managed systems, at low levels of N use.
<b>PFP</b> = Partial factor productivity of applied nitrogen (kg harvested product per kg N applied)	$PFP = Y / F$ or $PFP = Y_0 / F + AE$	<ul style="list-style-type: none"> <li>Important for farmers, because it integrates the use efficiency of indigenous and applied N</li> <li>High indigenous soil N supply (high <math>Y_0</math>) and high AE are equally important for PFP</li> </ul>	40 – 80 kg/kg; > 60 kg/kg in well-managed systems, at low levels of N use.

3) F = amount of fertilizer N applied, kg per ha.

$Y_0$  = crop yield in a control treatment with no fertilizer N applied, kg per ha.

$Y_N$  = crop yield with applied fertilizer N, kg per ha applied.

$U_0$  = total N uptake in aboveground biomass at maturity, without applied fertilizer N, kg per ha.

$U_N$  = total N uptake in aboveground biomass at maturity, with applied fertilizer N, kg per ha.

**Annex 2. Comparison of the current EUROSTAT/OECD approach for estimating Gross Nitrogen Balances (GNB), with an ‘ideal approach’ and a ‘practical approach’ according to EUROSTAT (2013).**

Current GNB	Ideal GNB	Practical GNB
<b>INPUTS</b>		
N1) Mineral fertilizers	N1) Mineral fertilizers	N1) Mineral fertilizers
N2) Manure production	N2) Manure production	N2) Manure production
N3) Net manure import/export, withdrawals, stocks	N3) Net manure import/export, withdrawals, stocks	N3) Net manure import/export, withdrawals
N4) Other organic fertilizers	N4) Other organic fertilizers	N4) Other organic fertilizers
N5) Biological N fixation	N5) Biological N fixation	N5) Biological N fixation
N6) Atmospheric N deposition	N6) Atmospheric N deposition	N6) Atmospheric N deposition
N7) Seed and planting materials	N7) Seed and planting materials	N7) Seed and planting materials
	N8) Crop residues inputs	
N9) <b>Total inputs</b> = sum (N1,N2,N3,N4,N5,N6,N7)	N10) <b>Total inputs</b> = sum (N1,N2,N3,N4,N5,N6,N7,N8)	N11) <b>Total inputs</b> = sum (N1,N2,N3,N4,N5,N6,N7)
<b>OUTPUTS</b>		
N12) Crop production	N12) Crop production	N12) Crop production
N13) Fodder production	N13) Fodder production	N13) Fodder production
N14) Crop residues outputs	N14) Crop residues outputs	N16) Residues removed /burnt
	N15) Stock changes of N in soil	
N17) <b>Total outputs</b> = sum (N12, N13, N14)	N18) <b>Total outputs</b> = sum (N12, N13, N14, N15)	N19) <b>Total outputs</b> = sum (N12, N13, N16)
<b>SURPLUS</b>		
N20) <b>GNS</b> = N9 – N17	N21) <b>GNS</b> = N10 - N18	N24) <b>GNS</b> = N11 - N19
	N22) <b>aGNS</b> = N gas emissions	N22) <b>aGNS</b> = N gas emissions
	N23) <b>hGNS</b> = N21 – N22	N25) <b>hGNS</b> = N24 - N22