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Indicators to evaluate agricultural nitrogen efficiency of the 27 member states of the European Union

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ABSTRACT

Nitrogen (N) use in European agriculture is not efficient, with less than one third of available N recovered in intended outputs. Over two thirds of N is lost to the environment, where it has negative ecological, social and economic consequences. Improving N efficiency in crop and animal production is a priority to reduce its detrimental effects while maintaining food production. The territory scale is particularly suitable for evaluation of N efficiency because it is used for environmental impact assessment and public policies. However, N Use Efficiency (NUE), the efficiency indicator available at this scale, has several limitations: (i) inputs and outputs can vary depending on the boundaries and definitions used, (ii) input production and transport are not always included, and (iii) changes in soil N stock are rarely considered. Three indicators were recently developed at the farming system scale to overcome NUE limitations. System N efficiency (SyNE) expresses N in intended outputs as a function of all major N inputs and losses. Relative N efficiency (RNE) expresses N efficiency relatively to its potential given the nature of productions. System N balance (SyNB) expresses N losses from cradle to the gate of the farm. All three indicators include N losses due to the production and transport of inputs and soil N stock variations. The current study tested these indicators at the national scale to provide a better understanding of N management in 27 European countries. The study demonstrates the feasibility and utility of calculating these indicators at the national scale. The mean NUE of European countries is 0.35, while their mean SyNE is 0.23, highlighting the importance of considering soil N loss in efficiency indicators. Average SyNB is 113 $kgN\,ha^{-1}$ AA, but varies from 31 to 432 $kgN\,ha^{-1}$ AA, showing the large margin of progress of some countries regarding N losses. Mean RNE is 0.43, which means that European countries could maintain their production with much less N inputs. The systems approach enables relevant comparisons among countries with different production methods and intensities. Combining SyNE and SyNB provides complementary information about the agricultural use of N resources and the resulting environmental pressure. RNE assesses the progress margin of each country based on its production and enriches the efficiency analysis by considering the nature of agricultural products. These indicators are promising tools to study, compare and improve the N efficiency of territories or countries.

1. Introduction

The European Union (EU) is one of the most intensive agricultural regions per unit of surface area (Haberl et al., 2007; Monfreda et al., 2008). This productivity is supported by the massive use of agricultural inputs, mostly nitrogen (N) fertilizers (Mueller et al., 2012) and imported feedstuff (Lassaletta et al., 2014). However, only 31% of agricultural N inputs are recovered in intended products at the European scale (Leip et al., 2011b). This low N efficiency results in major N losses, which have problematic impacts on water, air and soil quality as well as ecosystem functions, biodiversity and human health (Sutton et al., 2011). Rockstrom et al. (2009) identified the disruption of the biogeochemical N cycle as one of the main threats to future human development. Improving N efficiency, defined as the ratio between N in intended agricultural products and N used to produce them, is crucial to reduce this environmental impact while also providing enough food, feed, fuel and fiber to the growing population (Sutton et al., 2011).

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The territory scale is a particularly important research challenge. It integrates all biogeochemical flows and provides additional solutions compared to those at smaller scales (e.g. manure exchange, landscape management, wastewater treatment). It allows analysis of specific national agricultural trends and policies, such as the EU Common Agricultural Policy (Velthof et al., 2014) to prioritize actions that limit environmental risks (Leip et al., 2011a). Indicators that quantify N efficiency are necessary to improve it at the territory scale.

Most N management indicators at the territory scale focus on estimating N losses through modeling approaches (Moreau et al., 2013) or N balances such as the farm-gate balance (FGB; Dalgaard et al., 2012). N footprint indicators (Galloway et al., 2014) have also been developing recently. They consider the whole food chain (input and food production, food processing and consumption), and can include other human activities such as energy use. The most used N efficiency indicator is called nitrogen use efficiency (NUE; Leip et al., 2011b; Liu et al., 2008). This indicator is recommended as an agro-environmental indicator for the Common Agricultural Policy (European Commission, 2000). The United Nations Economic Commission for Europe considers it a legal tool for implementing the Gothenburg Protocol on air pollution (UNECE, 2012). However, both FGB and NUE have several limitations:

- Considered inputs and outputs can vary depending on the boundaries and definitions used by the authors. For instance, manure output can be considered an output, a negative input or is ignored in indicators calculation (Dalgaard et al., 2012; Simon et al., 2000; Spears et al., 2003)
- N emitted during production and transport of inputs is not always included (Schröder et al., 2003; Sutton et al., 2013)
- changes in soil N are rarely considered in the calculation of indicators due to the lack of data (de Vries et al., 2011; Özbek and Leip, 2015)
- NUE is calculated as a ratio between N outputs and inputs. Thus, if the same quantity of N is added on both input and output sides, the ratio tends towards one. This mathematical bias favors farms that buy animal feed and sell crops against those that feed their animals with their crops (Godinot et al., 2014; Schröder et al., 2003).

A novel indicator, system nitrogen efficiency (SyNE; Godinot et al., 2014), is based on NUE but resolves its limitations. SyNE presents some similarities with existing N footprint indicators, but focuses on the efficiency of agricultural systems to transform N inputs into intended N outputs, while N footprint indicators usually focus on N losses due to the consumption patterns of end-consumers. Similarly, system nitrogen balance (SyNB; Godinot et al., 2014) is based on FGB and resolves its limitations. As the novel indicators are based on existing indicators that have been used at the territory scale, they should also be applicable to this scale.

Several authors claim that N efficiency is linked to the type of production system considered (Schröder et al., 2003; UNECE, 2012). By nature, a farming system or a territory with mostly animal production will be less efficient than a system with mostly crops. The relative nitrogen efficiency (RNE) indicator addresses these biological differences by expressing efficiency relative to the maximum attainable efficiency of each product (Godinot et al., 2015).

The goal of this study was to apply the three indicators presented above (SyNE, SyNB and RNE) to the 27 member states of the EU to test their ability to describe N management at the territory scale and each member state's progress margin in N efficiency.

Table 1
Attainable nitrogen efficiency of selected agricultural products (from Godinot et al., 2015). Products in parentheses were assumed similar to products of the same line.

Product type	Attainable efficiency
Beef cattle (+ horses and small ruminants)	0.26
Byproducts: honey, wool	1.00
Crops	0.90
Milk (all species)	0.39
Eggs	0.48
Pig	0.49
Poultry (+ rabbit)	0.59

2. Materials and methods

2.1. Indicator calculation

SyNE, SyNB and RNE were calculated at the national scale, as follows:

$$SyNE = \frac{\sum_{i=1}^{n} net\ output_i}{\sum_{j=1}^{m} net\ input_j + \sum_{k=1}^{p} indirect\ loss_k - \Delta N_{soil}}$$

$$SyNB = \sum_{j=1}^{m} net\ input_j + \sum_{k=1}^{p} indirect\ loss_k - \Delta N_{soil} - \sum_{i=1}^{m} net\ output_i$$

$$attainable\ efficiency = \frac{\sum_{i=1}^{n} net\ output_i}{\sum_{i=1}^{n} net\ output_i / attainable\ efficiency_i}$$

$$RNE = \frac{SyNE}{attainable\ efficiency}$$

where: $\sum_{i=1}^{n} net\ output_i$ is the sum of the n net N outputs by crops and animal products, $\sum_{j=1}^{m} net\ input_j$ is the sum of the m net N inputs from organic and inorganic fertilizers, feed, seeds, manure, biological N fixation, atmospheric deposition and direct emissions from fuel combustion, $\sum_{k=1}^{p} indirect\ loss_k$ is the sum of the p net N losses from feed, livestock, seeds, inorganic fertilizers and fuel production and transport, ΔN_{soil} is the annual change in soil organic N (positive when N is stored in the soil and negative when soil N is used) $attainable\ efficiency_i$ is the maximum attainable efficiency for product i (Table 1)

Fig. 1 illustrates differences between the calculation of NUE and FGB (Fig. 1a) and the calculation of SyNE and SyNB (Fig. 1b). The latter are calculated from net flows, always consider manure as an input, include indirect N losses due to input production and transport and account for changes in soil N.

Attainable efficiency values used to calculate RNE (Table 1) are based on the highest references at the farm scale from a literature review. They represent the highest currently known efficiency limits for different productions, and will need to be updated according to new technical innovations. They also include the best recycling practices for manure and crop residues from the literature. Recycling increases production efficiency because it replaces other N inputs.

Attainable efficiencies of less common products were assumed to equal those of similar but more common products. Horses and small ruminants produced for meat were considered similar to beef cattle; dairy sheep and goats were considered similar to dairy cows; and rabbits were considered similar to poultry. Wool was considered a byproduct of sheep milk and meat and was given an efficiency of 1.00. This means that all metabolic costs and associated losses are attributed to milk and meat. Similarly, honey was considered a crop byproduct and was given an efficiency of 1.00.

2.2. Data used to calculate N flows at the national scale

All data were collected from 2000 to 2008 for each of the 27 EU member states. Since Croatia recently entered the EU, reliable data