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SyNE: An improved indicator to assess nitrogen efficiency of farming systems

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ABSTRACT

Reactive nitrogen (N) flows (all forms of N except N_2) are greatly increasing worldwide. This is mainly due to the ever larger use of inorganic N fertilizers used to sustain the growing food production. N flows have major impacts on water, air and soil quality as well as on biodiversity and human health. Reconciling the objectives of feeding the world and preserving the environment is a great challenge for agriculture. One of the main ways to increase food production while reducing its detrimental effects is to increase the efficiency of N use.

N use efficiency (NUE) is a commonly used indicator to estimate efficiency of N use at the farm scale. It is defined as the ratio of farm N outputs to N inputs. However, it has some inconsistencies and biases, which raises questions about its reliability for assessing N efficiency of farming systems. As a consequence, we propose a new indicator, called system nitrogen efficiency (SyNE), which is based on NUE and improves upon it in several ways. First, life cycle inventory references are used to estimate N emissions linked to the production of inputs outside the farm. Second, net N flows are calculated by subtracting inputs and outputs of the same product in the farming system. Third, manure is not considered an end product, unlike crop and animal products. Finally, the annual change in N in soil organic matter is estimated.

SyNE therefore expresses the efficiency of a farming system in transforming N inputs into desired agricultural products. It takes into account all sources of N, including the annual change in soil N stock as well as N losses occurring during the production and transport of inputs.

To test the relevance of this new indicator, 38 mixed farms were surveyed in Brittany, France, and their NUE and SyNE were calculated and compared. Sensitivity analysis was performed to estimate the contribution of each variable to both indicators. We demonstrate SyNE is a useful indicator for comparing the N efficiency of different farming systems. We discuss its use in combination with system N balance (SyNB), a N loss indicator at the system scale. The combination of both indicators gives a more reliable estimate of the productive efficiency and potential environmental impacts of N in various farming systems.

1. Introduction

1.1. The challenge of nitrogen efficiency

The great increase in reactive nitrogen (N) flows (all forms of N except N_2) on the Earth is mainly due to the production of N fertilizer through the Haber-Bosch process (Galloway et al., 2008). Inorganic N fertilizers have a major influence on food production: Smil (2002) estimated that 40% of the world population depends on them for their food, a proportion that is still growing. However, this disturbance of the N cycle due to human production of reactive N causes negative impacts on water, air and soil quality as well as on biodiversity and human health (Sutton et al., 2011). These negative impacts imply the need to design and implement mitigation measures to ensure human well-being and agricultural sustainability.

To this end, improving N efficiency in animal and crop production is one main goal identified by recent studies on nutrient flows (Foley et al., 2011; Galloway et al., 2008; Sutton et al., 2011). N efficiency can be defined as the extent to which N inputs are converted into N outputs.

1.2. Why a new N indicator at the farm-level?

The farming system is defined here as "an organized decision-making unit comprising the farm household, cropping and

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livestock systems, that transform land, capital and labor into useful products that can be consumed or sold" (Fresco and Westphal, 1988). It is a pertinent level at which to study N use in agriculture and its fate. Indeed, it is the level at which many farmers' decisions occur (Sutton et al., 2011) and regulations can be implemented (e.g., EU Nitrate Directive 91/676/EEC). Currently, two N indicators are widely used to assess N use at the farm level: farm-gate balance (FGB) and N use efficiency (NUE) (Halberg, 1999).

FGB is calculated as the difference between N imported into the farm (N inputs) and N exported from the farm (N outputs; Eq. (1)). A positive result is called nitrogen surplus (NS).

$$FGB = N\ inputs - N\ outputs \quad (1)$$

When applied to a farm considered as a black box, FGB assesses potential N losses from the farm (Vellinga et al., 2011). It is also a tool for assessing environmental regulations and policies (OECD and EUROSTAT, 2007; Schröder and Neeteson, 2008). According to UNECE (2012), FGB is a useful tool for optimizing N management at the farm level. However, FGB is an environmental indicator that is not related to production. Moreover, it gives only rough indications about how to improve N management.

NUE has been applied at the farm level for over 20 years (Aarts et al., 1992) and is based on the same components as FGB:

$$NUE = N\ outputs/N\ inputs \quad (2)$$

NUE was identified as a key indicator to achieve better nutrient use (Sutton et al., 2013), and therefore it is a tool to increase the efficiency of N use in agriculture. It expresses the link between agricultural production (animal products, crops) and associated resource consumption. NUE is thus a meaningful indicator for farmers, who can assess how well they convert inputs to outputs. However, it has several limitations:

1. Inputs and outputs used to calculate NUE differ among authors (Watson et al., 2002). This is particularly true for inputs whose estimation is complex or uncertain, such as symbiotic N fixation, atmospheric N deposition or changes in soil organic matter (SOM) stocks. Not considering all inputs and outputs does not satisfy the fundamental law of mass conservation, which is the main requirement for calculating NUE.
2. When NUE is calculated at the farm level, it excludes losses due to producing inputs, such as NO_3^- leached during the production of feed crops outside the farm, N_2O lost during fertilizer synthesis and NO_x emitted during transport. Up to 40% of nitrate (NO_3^-) emissions and 50% of N_2O emissions of agricultural production are therefore not considered in NUE since they occur outside the farm (Cederberg and Mattsson, 2000). Not taking these losses into account is equivalent to considering that input production is 100% N efficient. Consequently, it is always more efficient to buy inputs rather than produce them on-farm, which favors farms with greater reliance on external inputs.
3. Mathematically, NUE increases when the same value is added to both numerator and denominator; therefore, a "purchase-resale" management of N inputs and outputs increases it. For example, a farm that buys 10 kg N per ha of agricultural area (AA) more feed than another farm and sells 10 kg N ha AA^{-1} more crops has a higher NUE (Fig. 1). This leads to the questionable conclusion that relying on external inputs is more efficient than being self-sufficient (Schröder et al. 2003). Consequently, specialized crop or animal farms have a higher NUE than mixed farms (Schröder et al., 2003); however, many studies argue that mixed farming systems have lower N losses and higher NUE than specialized farms (Oomen et al., 1998; Wilkins, 2008)
4. NUE does not distinguish among outputs: by definition (Eq. (2)), 1 kg of N output as manure is equivalent to 1 kg of N output as animal or crop products. By considering that all N outputs have the same quality, NUE expresses the efficiency of minimizing N losses, not of producing agricultural products.
5. NUE is based on the assumption that SOM content does not vary at an annual scale (Schröder et al., 2003; Watson and Atkinson, 1999), which simplifies calculations. This can result, however, in unsustainable management of soil fertility if N uptake by crops relies on mineralized (and therefore decreasing) SOM or in overestimation of N losses if part of the unaccounted N flows is stored as SOM.

The aim of the present study was to develop and test a new indicator, called system nitrogen efficiency (SyNE), which addresses these limitations to improve estimation of N efficiency at the farm level.

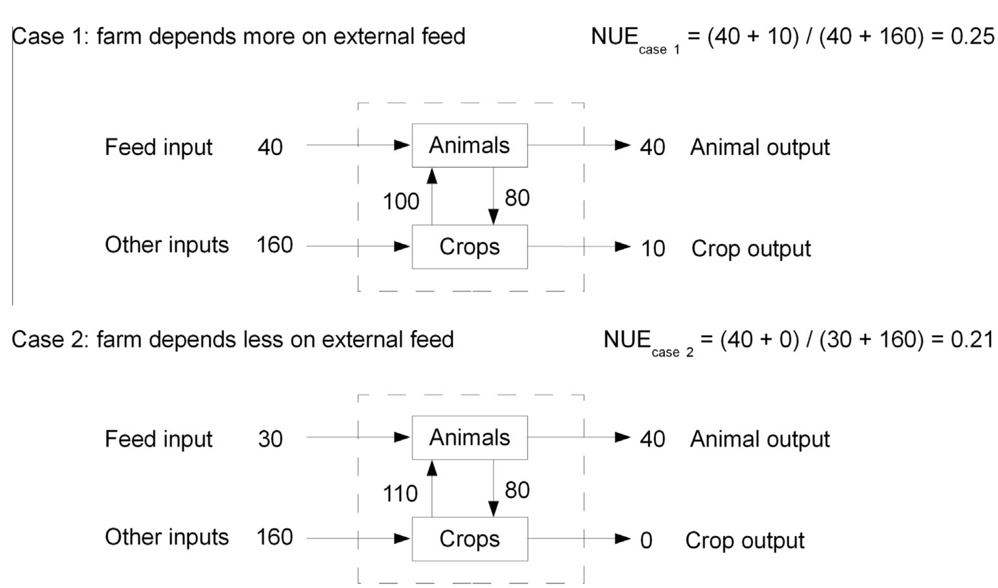

Fig. 1. The "purchase resale" bias of the nitrogen use efficiency (NUE) indicator. Arrows represent N inputs and outputs in kg N per ha of agricultural area. The dashed box represents the farm perimeter. NUE is calculated according to Eq. (1).