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

Olivier Godinot, Matthieu Carof, Françoise Vertès, Philippe Leterme

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O. Godinot^{a,b,c}, M. Carof^{a,b,c}*, F. Vertès^{b,a}, P. Leterme^{a,b,c}

^a AGROCAMPUS OUEST, UMR1069 SAS, F-35042 Rennes, France

^b INRA, UMR1069 SAS, F-35042 Rennes, France

^c Université européenne de Bretagne, France

* Corresponding author: matthieu.carof@agrocampus-ouest.fr, AGROCAMPUS OUEST, 65 rue de Saint-Brieuc, CS 84215, F-35042 Rennes cedex, +33 (0)2 23 48 54 77

Abstract

Reactive nitrogen (N) flows (all forms of N except N₂) 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.

Keywords: nitrogen efficiency, life cycle analysis, soil nitrogen, farming system, indicator

1. Introduction

1.1. *The challenge of nitrogen efficiency*

The great increase in reactive nitrogen (N) flows (all forms of N except N₂) on the Earth is mainly due to the production of N fertilizer through the Haber-Bosch process (Galloway et al., 2008; Smil, 1999; Sutton and Reis, 2011). 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 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 (Halberg et al., 1995; 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; Equation 1). A positive result is called nitrogen surplus (NS).

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

When applied to a farm considered as a black box, FGB assesses potential N losses from the farm (Halberg et al., 1995; Jarvis, 2001; Vellinga et al., 2011). It is also a tool for assessing environmental regulations and policies (OECD and EUROSTAT, 2007; Ondersteijn et al., 2002; 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:

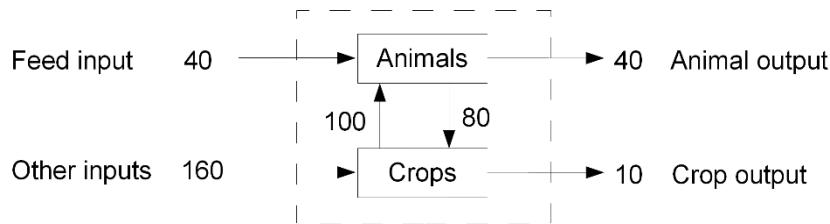
$$\text{NUE} = \text{N outputs} / \text{N inputs} \quad (2)$$

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 (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..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 (Equation 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.

Case 1: farm depends more on external feed

$$NUE_{\text{case 1}} = (40 + 10) / (40 + 160) = 0.25$$



Case 2: farm depends less on external feed

$$NUE_{\text{case 2}} = (40 + 0) / (30 + 160) = 0.21$$

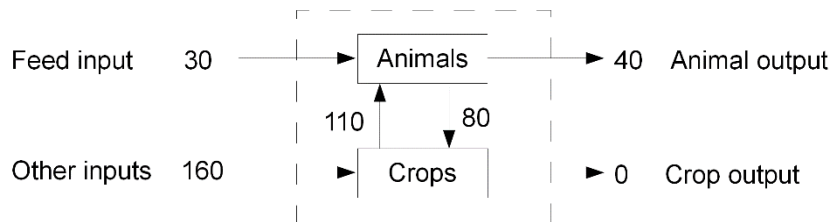


Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1. The “purchase resale” bias of the nitrogen use efficiency (NUE) indicator

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 equation 1.

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.

2. Material and Methods

2.1. Farm survey data used for indicators calculation

Thirty-eight mixed dairy-crop farms in southeastern Brittany, France, were surveyed in spring 2012 to collect information about their N inputs, N outputs and internal N flows. Farmers were asked about crop areas and yields, herd composition, sales of animal products and crops, feed and fertilizer purchases, manure management, and all other information related to N flows in the farming system for the calendar year 2011. Mean values were preferred over exact values to better estimate average N balance. From these data, NUE was calculated for each farm and, step-by-step, converted to SyNE and compared to NUE.

2.2. Development of the SyNE indicator

2.2.1. Contribution of the life cycle assessment approach to setting system boundaries

To account for all N losses due to the production and transport of inputs (*i.e.* “indirect” losses), system boundaries of the farm were enlarged compared to NUE (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..2) according to the principles of agricultural life cycle assessment (LCA), *i.e.* “from cradle to farm gate” (Cederberg and Mattsson, 2000).

As a consequence, N losses (kg N ha AA⁻¹) during the production of inputs were included in calculations of SyNE.

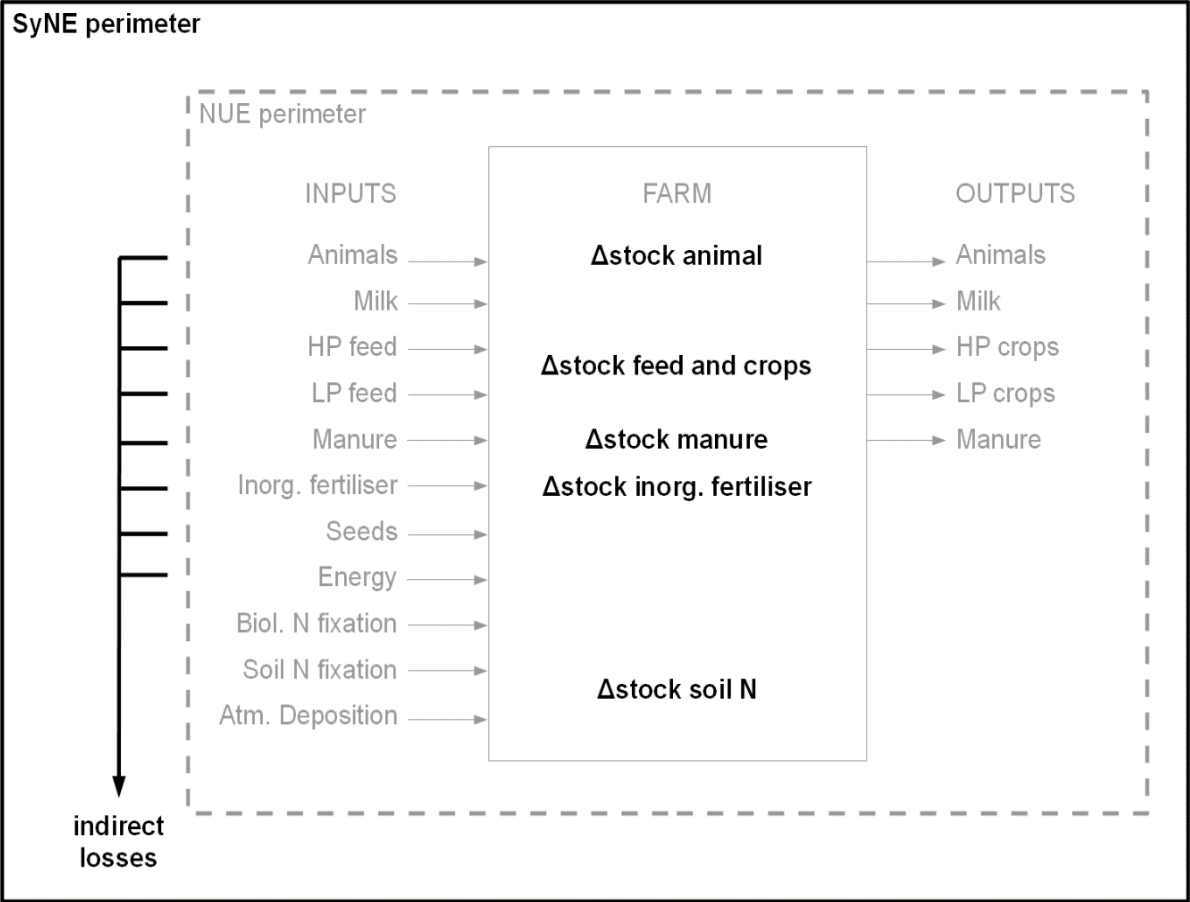


Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..2. **Perimeter of NUE and SyNE**

The dashed-line box represents the perimeter used to calculate NUE. The solid-line box represents the perimeter used to calculate SyNE. Bold black items are specific to SyNE. Arrows represent flows of N. HP, high-protein; LP, low-protein; Δstock, change in stock; Inorg., inorganic; Biol., biological; Atm., atmospheric.

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1. **Reference values used for N contents, indirect (i.e., outside of farm) N losses and N fixation of inputs and outputs**

Product	% DM ^a	N content ^a	Indirect N losses	Unit
Alfalfa, dried	91	29.3	2.1 ^b	kg N Mg DM ⁻¹
Alfalfa, N fixation		32.0 ^c		kg N fixed Mg DM ⁻¹
Alfalfa, seed	87 ^d	38.2 ^d	18.1 ^b	kg N Mg DM ⁻¹
Ammonium nitrate	100	335.0	8.2 ^e	kg N Mg DM ⁻¹
Ammonium sulfate	100	260.0	0.4 ^e	kg N Mg DM ⁻¹
Animals, live		24.0 ^f	101.1 ^b	kg N Mg liveweight ⁻¹
Barley, grain	87	18.9	10.3 ^b	kg N Mg DM ⁻¹
Barley, seed	87 ^g	18.9 ^g	10.3 ^e	kg N Mg DM ⁻¹
Concentrate compound, 41% protein	88 ^h	74.5	21.1 ^b	kg N Mg DM ⁻¹
Concentrate compound, 18% protein	87 ^g	33.1	46.3 ^b	kg N Mg DM ⁻¹
Maize gluten feed	88	34.7	11.5 ^b	kg N Mg DM ⁻¹
Diammonium phosphate	100	180.0	0.6 ^e	kg N Mg DM ⁻¹
Fuel		19.0 ⁱ	1.4 ^e	kg N m ⁻³
Grass, hay	85 ^j	15.0 ^j	6.1 ^e	kg N Mg DM ⁻¹
Grass, seed	87 ^g	18.9 ^g	8.2 ^e	kg N Mg DM ⁻¹
Linseed meal	91	55.0	30.9 ^b	kg N Mg DM ⁻¹
Maize, grain	86	15.0	11.4 ^b	kg N Mg DM ⁻¹
Maize, seed	86 ^k	15.0 ^k	45.1 ^e	kg N Mg DM ⁻¹
Maize, silage	33	11.2	4.3 ^e	kg N Mg DM ⁻¹
Manure, chicken		15.0 ^j		kg N Mg fresh weight ⁻¹
Manure, dairy cow		5.5 ^j		kg N Mg fresh weight ⁻¹
Milk		5.2		kg N Mg FPCM ⁻¹
Miscanthus, stems only	85 ^l	1.6 ^l		kg N Mg DM ⁻¹
Oats, grain and seed	88 ^m	17.6 ^m	11.4 ^b	kg N Mg DM ⁻¹
Oilseed rape grain	92	33.4		kg N Mg DM ⁻¹
Oilseed rape seed	92 ^m	33.4 ^m	29.5 ^e	kg N Mg DM ⁻¹
Pea, N fixation		32.0 ⁿ		kg N fixed Mg DM ⁻¹
Pea, grain	87	38.2	21.2 ^e	kg N Mg DM ⁻¹
Pea, seed	87 ^m	38.2 ^m	18.1 ^e	kg N Mg DM ⁻¹
Rapeseed meal	89	61.3	8.0 ^e	kg N Mg DM ⁻¹
Red clover, N fixation		28.0 ^o		kg N fixed Mg DM ⁻¹
Sewage sludge		3.5-17.0 ^p		kg N m ⁻³
Slurry, average pig prod.		3.5 ^j		kg N m ⁻³
Soybean meal	88	82.9	9.0 ^b	kg N Mg DM ⁻¹
Soybean meal, formaldehyde treated, 41% protein	88 ^h	74.5	10.9 ^b	kg N Mg DM ⁻¹
Triticale, grain and seed	87 ^m	18.7 ^m	9.7 ^b	kg N Mg DM ⁻¹
Urea	99	460.0	2.4 ^e	kg N Mg DM ⁻¹
Urea – ammonium nitrate		390.0	9.7 ^b	kg N m ⁻³
Wheat, grain	87	20.2	10.1 ^b	kg N Mg DM ⁻¹
Wheat, seed	87 ^m	20.2 ^m	16.0 ^e	kg N Mg DM ⁻¹
Wheat, straw	91	6.7	2.0 ^b	kg N Mg DM ⁻¹
White clover, N fixation		38.0 ^o		kg N fixed Mg DM ⁻¹

FPCM: Fat and Protein Corrected Milk; ^a Dry matter (DM) percentages and N contents are taken from INRA et al. (2013) unless specified; ^b UMR 1069 SAS, unpublished results; ^c Thiébeau et al., 2004; ^d based on pea seed value; ^e Nemecek and Kägi, 2007; ^f Bassanino et al., 2007; ^g based on barley grain value; ^h based on soybean meal value; ⁱ reactive N created by atmospheric combustion; ^j CORPEN, 1988; ^k based on maize grain value; ^l Monti et al., 2008; ^m seed based on grain value; ⁿ Mahieu et al., 2009; ^o Rasmussen et al., 2012; ^p 38-farm sample from this study.

For our 38 mixed farms sample, emissions of all forms of reactive N to soil, water and air during the production and transport of inputs were converted to kg N and expressed as kg N per Mg of product DM (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1). National data were used for most crops and feeds; for seeds and fertilizers, data were taken from a Swiss inventory (Nemecek and Kägi, 2007). Soybean meals from South and Central-West regions of Brazil were used to represent the mix used in France. N losses of meals and maize gluten feed were allocated according to the economic values of co-products. We chose not to include indirect N losses due to manure production. N losses during excretion and storage of manure were assigned to the farm producing manure.

In order to avoid double counting of indirect losses, we calculated net input (see section 2.2.2.) and only accounted for net indirect losses relative to net input production, as follows:

$$\text{Net indirect losses} = \text{net input} / \text{total input} * \text{indirect losses}$$

2.2.2. Avoiding the “purchase-resale” bias by calculating net input/output

To correct the “purchase-resale” bias of NUE (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1), we calculated net input or net output when similar products (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..2) were both entering and going out of the same farm. Net flows of similar products were calculated as:

$$\text{Net flow} = \text{input} - \text{change in stock} - \text{output}$$

If net flow is positive, it is considered a net input. If net flow is negative, its absolute value is considered a net output.

Some authors working on specialized dairy farms used a different method: they calculated net feed input (*i.e.* feed input minus crop output) (Aarts et al., 2000; Halberg et al., 1995), which was usually positive but can be negative (Dalgaard et al., 2012). However, in mixed farming systems, where crops can represent a large percentage of farm activities, it is not meaningful to express crop output as a negative feed input (*i.e.* crops are not necessarily produced for animal feed). Therefore, we express the net feed/crop balance as net input or net output where necessary. Moreover, two categories each were distinguished for feed and crops based on crude protein content (crude protein > or ≤ 15% DM). This prevents subtracting produced wheat from purchased soybean, since the former cannot replace the latter. We used the same reasoning for milk and animals, but we made a different choice for manure and soil N stock variation (see Sections 2.2.3. and 2.2.4.).

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..2. **Inputs and outputs considered deductible when calculating net flows**

Input category	Output category
Animals	Animals
Milk powder; whey; other milk byproducts	Milk
High-protein feed ^a : oilseed grains, meal and cake; legume grains; pure legume forage (silage, hay, dried); forage rape and kale; dried distillers grain, cereal gluten feed and meal, wheat bran; vinasses; animal byproducts (meat, blood, bones, fish meal, etc.); amino acids; ammonia; urea	High-protein crops: oilseed grains; legume grains; pure legume forage (silage, hay, dried); forage rape and kale
Low-protein feed ^a : cereal grains and all byproducts not mentioned as high-protein feed; all forages not mentioned as high-protein feed; sugar beet, sugarcane and its byproducts; potato and its byproducts; oils and fat; starch; straw	Low protein crops: cereal grains; all forages not mentioned as high-protein crops; sugar beet and sugarcane; potato, straw; fruits and vegetables; all crops not mentioned as high-protein crops
Manure, compost, sewage sludge, other organic fertilizers	Manure, compost, other organic fertilizers

^a High- and low-protein feeds have crude protein contents > and ≤ 15% DM, respectively

2.2.3. Considering only end products

Defining the status (*i.e.* utility) of outputs is important for calculating SyNE. In this paper, we wanted to design an indicator that can estimate the efficiency with which inputs are transformed into end products. We define end products as the final outcome of agricultural production, intended for human use. This mainly includes food, fiber, biofuel and other non-food products. Some authors suggest excluding manure output from the N efficiency calculation, as it is not an end product for human use (Aarts et al., 2000; Dalgaard et al., 2012; Simon et al., 2000). However, the status of manure varies from a waste to eliminate (excess nutrients in most intensive livestock regions) to a highly valuable resource (organic fertilizer in intensive crop regions with low SOM). Therefore, when manure output exceeds manure input, we represent it as a negative net input instead of a positive net output. Manure export is therefore considered to offset a given farm's inorganic fertilizer input.

2.2.4. Accounting for changes in stocks

The steady state assumption for SOM is not valid in many regions, including Brittany (Lemercier et al., 2006).

For our 38 mixed farms sample, we used AMG, a simulation model requiring few data, to simulate soil carbon dynamics (Andriulo et al., 1999; Saffih-Hdadi and Mary, 2008). AMG distinguishes two pools of SOM: the active pool and the stable pool, which the model never modifies. The active pool is mineralized at a rate of $k\%$ per year. At the same time, it is also enriched by crop residues, manure and organic fertilizers, at the rate of $k_1\%$ per year, depending on the humification potential of each input. The difference between mineralization and humification gives the annual net change in SOM (kg N ha^{-1}).

We used AMG model parameters given by Saffih-Hdadi and Mary (2008) with a constant C:N ratio of 10 for organic matter to predict the change in soil N. Initial SOM content, texture and

limestone content were taken from the French database of soil analyses (GIS Sol, 2013) at the canton level (French administrative unit, mean size 140 km²). Mean soil temperature was obtained from the closest meteorological station of INRA, located in Rennes, Brittany, France. Crop distribution in 2011 was considered to represent the average situation for all farms surveyed. Crop yields, surface areas and the fate of crop residues were used to estimate the amount of C returned to the soil by crops (Boiffin et al., 1986). For permanent grasslands, we assumed that roots returned 5 Mg DM ha⁻¹ year⁻¹ (Nguyen, 2003) and that above-ground biomass returned 20% of grassland yield (Vertès and Mary, 2007). For temporary grass leys, we used the same values but subtracted 5 Mg DM ha⁻¹ (equivalent to 200 kg N ha⁻¹) once in the lifetime of the ley to account for organic matter mineralization after ley destruction (Vertès et al., 2007). The amounts of C and N added to the soil in manure applications were also estimated. Soil N stock variation is not an end product for human use. Similar to manure (see Section 2.2.3.), it was always considered a net input, be it positive or negative. An increase in soil N stock was therefore considered to offset a given farm's organic fertilizer input. Other changes in N stocks include those in feed, harvested crops, manure, inorganic fertilizer, seeds and livestock. Stock variations can be important from one year to another and should therefore be considered. However farmers usually do not increase their stocks over several years. As this information was not available in our one-year survey, we assumed no changes in any of these N stocks, like Leip et al. (2011b), who considered that fertilizer purchases equaled fertilizer applications when using three-year averaged data.

2.2.5. SyNE equation

SyNE (unitless) equals net N outputs divided by net N inputs:

$$\text{SyNE} = \frac{\sum \text{net outputs}}{\sum \text{net inputs} + \sum \text{net indirect losses} - \Delta \text{Nsoil}} \quad (3)$$

Like SyNE, FGB was modified using the same hypotheses for inputs and outputs into an indicator of system N balance (SyNB) to consider the entire farming system perimeter:

$$\text{SyNB} = \sum \text{net inputs} + \sum \text{net indirect losses} - \Delta \text{Nsoil} - \sum \text{net outputs} \quad (4)$$

SyNB is expressed in kg N ha AA⁻¹.

2.3. Estimating N inputs and outputs for the 38 farms sample

The following N inputs were estimated: inorganic fertilizers, feed and litter, biological N fixation (BNF), imported manure, atmospheric deposition, non-symbiotic fixation, seeds, and petroleum products. Inorganic fertilizer quantities were converted to N using their N contents (from farm surveys). Feed and litter N inputs were estimated from the mean annual quantities bought and sold (farm surveys) and their N contents (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1). BNF was estimated as:

$$\text{BNF} = \text{area} \times \text{yield}_{\text{DM}} \times \% \text{legume}_{\text{DM}} \times \text{N}_{\text{fixed}}$$

where area (ha) is the surface with legume crops; yield_{DM} (Mg DM ha⁻¹) is harvested dry matter (DM) including legume and non-legume crops; %legume_{DM} is the percentage of legume in the

harvested DM; and N_{fixed} (kg N Mg DM⁻¹) is the amount of N derived from fixation per Mg of harvested legume DM. Areas and yields were obtained from the farm surveys, while percentage of legume at harvest was set at 100% for alfalfa, 20% for permanent grasslands (Agreste, 2010) and 20% for cereal-legume mixed crops. In mixed grass-clover leys, the percentage of clover was estimated following the protocol of Vertès and Simon (1991). Manure N was estimated using farm data when available or mean N content if not (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1). Wet and dry atmospheric deposition was set at 15 kg N ha⁻¹, representative of this part of Brittany (Ruiz et al., 2002). Non-symbiotic N fixation by free-living soil microorganisms was set at a constant value of 5 kg N ha⁻¹ (Smil, 1999). Seed N was approximated, assuming that all crops and grass leys were seeded with purchased seed, using mean French seed densities for 2011 (FAO, 2014). A constant value of 150 L ha⁻¹ of fuel was used to estimate input and consumption of petroleum products, based on a national average of 790 mixed dairy-crop farms (Bordet et al., 2010). Direct N emissions due to fuel combustion were estimated at 19 g N L⁻¹ from LCA references (Spriensma, 2004). No farmer in the surveys regularly bought animals; we thus set animal input at 0 kg N for all farms.

N outputs consisted of animals, crops, milk and exported manure. Animal and crop N outputs were estimated from the mean annual quantities sold (farm surveys) and their N contents (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1). Milk N output was expressed as fat-and-protein-corrected milk (FPCM), following the methodology of the Food and Agriculture Organization of the United Nations (FAO, 2010). Exported manure N was estimated using farm data when available or mean N content if not (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1).

2.4. Statistical analysis and sensitivity analyses

Descriptive statistics and sensitivity analyses were performed with R software (R Core Team, 2014). The latter were performed to estimate the influence of input variables on indicators of N efficiency (NUE and SyNE).

To test a wider range of values than that in our sample, a virtual sample of 1000 mixed farms was generated. Each variable was described with a distribution, a mean and a range (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..3). Distributions were determined from the 38-farm sample. Means were calculated from regional data (DRAAF Bretagne, 2011; Tirard, 2011). Mean changes in soil N stocks were calculated for all cantons in Brittany (GIS Sol, 2013). Mean feed inputs were estimated using national data from Rouillé et al. (2008). Ranges were defined to cover the extreme values observed in the 38 farm sample and other mixed dairy-crop farms in Brittany. No information was found about the distribution and range of atmospheric deposition, non-symbiotic fixation and fuel emissions. Fixed values described in chapter 2.3. were used for all farms. Therefore, as these parameters do not vary, they do not appear in the sensitivity analysis. From this description of variables, the virtual sample was created using the method described by Helton and Davis (2003). Random values were generated for each input variable with the Latin Hypercube Sampling method. Rank correlations from the 38 surveyed farms were used to correlate variables in the new virtual

sample. The resulting sample therefore had the same correlations as the 38 surveyed farms but a larger size and a broader range to better represent mixed-farm diversity.

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..3. **Distribution, mean and range hypotheses of input and output variables to calculate N use efficiency (NUE) and system N efficiency (SyNE) indicators in a virtual sample of 1000 mixed farms (kg N per ha agricultural area per year)**

Variable	Distribution	Mean	Range
Fertilizer input	normal	55.00 ^a	± 100%
Indirect fertilizer input	normal	1.22	± 100%
BNF	gamma	25.00 ^a	0 ; 122
HP feed input	normal	24.93 ^b	± 100%
Indirect HP feed input	normal	6.43	± 100%
Manure input	gamma	13.00 ^a	0 ; 82
LP feed input	gamma	7.30 ^b	-100% ; +200%
Indirect LP feed input	gamma	2.45	-100% ; +200%
Seed input	normal	0.91 ^c	± 50%
Indirect seed input	normal	1.16	± 50%
Change in soil N	lognormal	0.10 ^d	-168 ; 30
LP crop output	normal	28.29 ^c	± 100%
Milk output	lognormal	23.96 ^c	-50% ; +100%
Animal output	lognormal	5.30 ^c	-50% ; +100%
HP crop output	gamma	2.38 ^c	0 ; 42
Manure output	exponential	2.00 ^a	0 ; 15

^a Tirard, 2011; ^b Rouillé et al., 2008; ^c DRAAF Bretagne, 2011; ^d GIS Sol, 2013
BNF: biological N fixation; HP: high-protein; LP: low-protein

Global sensitivity analysis techniques generally assume parameter independence (Xu and Gertner, 2008), but since our study focused on N flows inside a farming system, many N input and output variables were strongly correlated. The method proposed by Xu and Gertner (2008) was used, since it can consider correlated variables. We decomposed the contribution of each variable to the variance in efficiency into “uncorrelated” and “correlated” (with all other variables) portions. The uncorrelated contribution to variance is the effect of only the variable under consideration on efficiency. The correlated contribution is the effect of only the correlations between the variable under consideration and all others on efficiency. This decomposition of variance into correlated and uncorrelated contributions gives a better understanding on the influence of each variable on efficiency than only total contribution to variance.

3. Results

3.1. Sensitivity analysis of 1000 virtual farms

The decomposition of variance into correlated and uncorrelated contributions identified three groups of variables (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..3). Influential variables, such as low-protein crop output, BNF, high-protein crop output and change in soil N stock, had a moderate-to-high uncorrelated contribution to variance as well as a strong positive correlated effect. Potentially influential variables, such as fertilizer input, milk output and manure input, had a significant uncorrelated effect but a negative correlated effect which reduced their total contribution to variance. All other variables had lesser influence, characterized by a small uncorrelated effect or only a correlated effect.

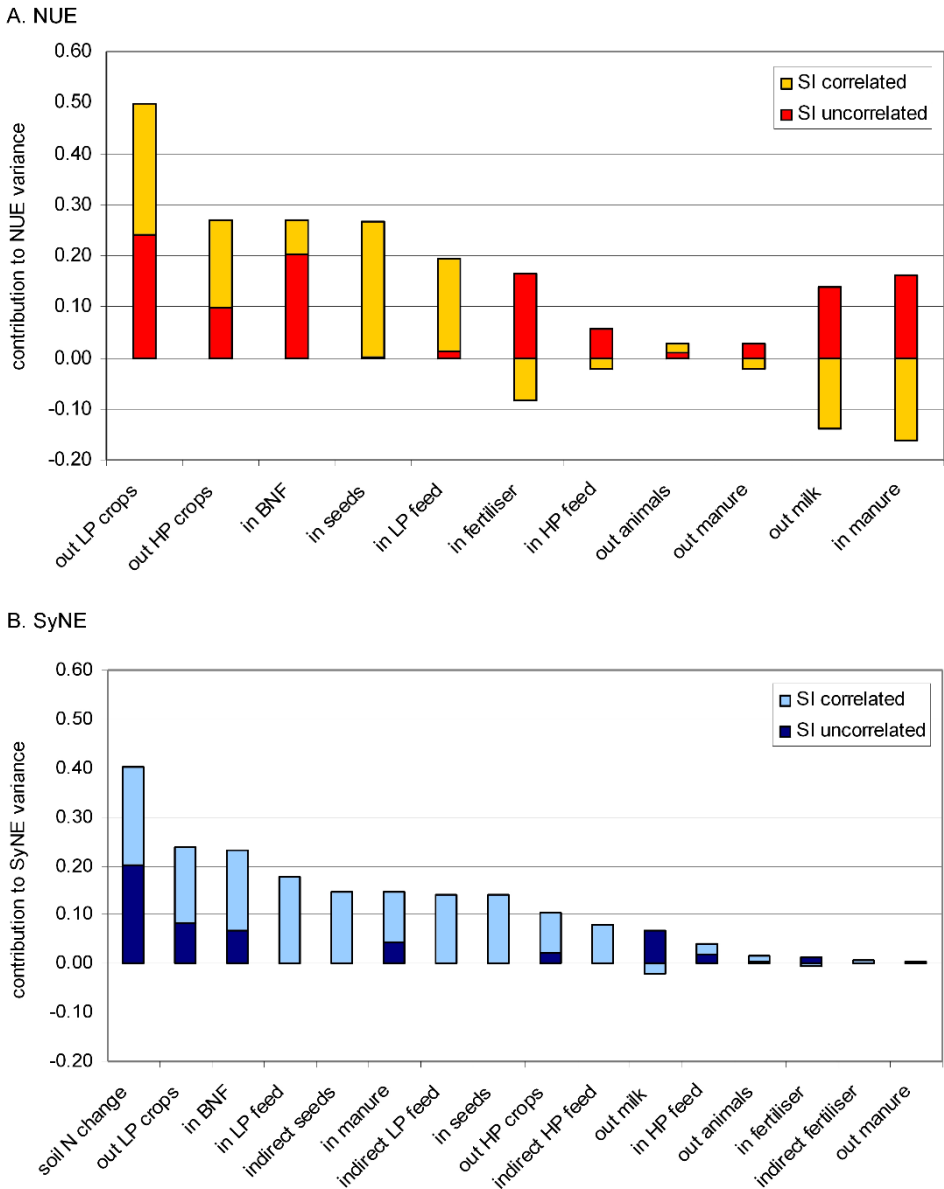


Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..3. Sensitivity of N efficiency indicators NUE (A) and SyNE (B) to farm input (in) and output (out) variables, divided into correlated (light) and uncorrelated (dark) contributions

Sensitivity indices (SI) are ranked by decreasing effect on total variance and expressed as a proportion of total variance in NUE or SyNE. Total sensitivity is greater than 1 due to correlation effects. BNF: biological N fixation; HP: high-protein; LP: low-protein.

The most influential variable on overall sensitivity of NUE was low-protein crop output, whereas it was soil N change for SyNE. Low-protein crop output was an influential variable for NUE and SyNE. Mean change in soil N stock was close to zero but had the largest range of all variables (198 kg N ha AA⁻¹), thus explaining its contribution to variance in SyNE. Although it was an influential variable for both indicators, BNF had a higher contribution to NUE variance than to SyNE variance. Due to its calculation method, SyNE had smaller net N outputs and larger net N inputs than NUE. Therefore, the contribution of inputs was smaller for SyNE than for NUE. High protein crop output had a great influence on NUE but a much smaller influence on SyNE. The calculation of net high protein output decreased its influence on the SyNE indicator. The uncorrelated influence of fertilizer and manure input as well as milk output was important on NUE, but it was significantly reduced by negative correlations. For SyNE, there were only very small negative correlations for fertilizer input and milk output.

The influence of low protein feed input was essentially due to its negative correlation with low protein crop output. Seeds correlated effect was mostly due to their high correlation with low protein crop output. Indirect losses were all very much correlated with their relative inputs, as illustrated by their small uncorrelated effect.

3.2. Characteristics of the 38 mixed farms surveyed

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..4 shows an important diversity of farms in the sample. One farm was much larger than the others, four were organic and three practiced zero-grazing for lactating cows. The percentage of forage and cash crops in the AA differed greatly between farms.

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..4. Main characteristics of the 38 mixed dairy-crop farms surveyed in 2012 in southeastern Brittany, France

Variable	Mean (SD)	Minimum	Maximum
Livestock units (LU)	103.3 (48.8)	44.6	300.4
Lactating cows	69.8 (34.3)	30.0	197.0
FPCM ^a per cow (kg cow ⁻¹ year ⁻¹)	8680 (1154)	5126	10,961
FPCM ^a sold (kg year ⁻¹)	596,456 (286,080)	246,001	1,669,098
Agricultural area (AA, ha)	108.3 (59.5)	47.2	367.0
Forage area (% AA)	67% (15%)	27%	93%
Stocking rate (LU ha forage ⁻¹)	1.5 (0.3)	1.1	2.6

^a FCPM: fat-and-protein-corrected milk

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..5 shows N inputs, N outputs and indirect N losses for the 38 mixed farms surveyed. Inorganic fertilizer was the main N input, which is consistent with other studies of dairy farms (Aarts et al., 2000; Bleken et al., 2005; Gourley et al., 2012; Simon et al., 2000). Its large variability is explained by the inclusion of four organic farms in the farm sample. BNF was the second largest input, also due to the farms sampled: all farms included alfalfa and/or clover in their forage area. Feed was also a major input; its mean value became greater than BNF when indirect N losses were taken into

account. Nearly all of feed N input (95%) was composed of high-protein feed, mainly soybean meal (39%), concentrate compound (28%) and rapeseed meal (24%). Half of the farms bought low-protein materials, mostly as wheat straw. Due to a lack of information, it was not possible to distinguish between forage straw and straw used for bedding; therefore all straw was considered low-protein feed. Sixteen percent of farms bought hay or forage maize and 8% cereal grains. Over 70% of farms also imported organic fertilizers, mostly as pig slurry and chicken manure. Due to a moderate mean stocking rate (1.5 LU ha⁻¹ fodder area), manure production was below the legal limit of 170 kg organic N ha AA⁻¹ (European Union Nitrate Directive) for all farms, thus allowing for manure import rather than inorganic fertilizer purchase. Mean milk output was 29.8 kg N ha AA⁻¹ and the main output for 16 farms (42%). Low-protein crops were the largest mean output (35.0 kg N ha AA⁻¹), showing the importance of crop production in the farm sample. Only three out of 38 farms (8%) sold no crops. Low-protein crops represented 85% of crop N outputs, and winter wheat represented 82% of low-protein crops sold. Oilseed rape represented 85% of high-protein crops.

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.. **5. Mean, standard deviation (SD), minimum and maximum N inputs and outputs calculated for 38 mixed dairy-crop farms surveyed in southeastern Brittany, France (kg N per ha agricultural area)**

	N flow			Indirect input N losses		
	Mean (SD)	Minimum	Maximum	Mean (SD)	Minimum	Maximum
Inputs						
Inorg. fertilizer	70.1 (36.1)	0.0	138.8	1.6 (0.8)	0.0	3.4
BNF	44.8 (25.3)	14.6	115.8	n/a	n/a	n/a
High-protein feed	37.7 (20.2)	0.0	93.2	9.7 (9.4)	0.0	45.7
Manure	20.0 (17.2)	0.0	59.4	n/a	n/a	n/a
Atm. deposition ^a	15.0 (0.0)	15.0	15.0	n/a	n/a	n/a
Soil N fixation ^a	5.0 (0.0)	5.0	5.0	n/a	n/a	n/a
Fuel ^a	2.8 (0.0)	2.8	2.8	0.2 (0.0)	0.2	0.2
Low-protein feed	2.3 (3.2)	0.0	12.2	0.8 (1.0)	0.0	3.9
Seeds	0.9 (0.2)	0.3	1.4	1.1 (0.3)	0.3	1.5
Animals	0.0	0.0	0.0	0.0	0.0	0.0
Outputs						
Low-protein crops	35.0 (19.6)	0.0	83.2			
Milk	29.8 (6.5)	19.3	42.1			
High-protein crops	6.1 (9.4)	0.0	40.7			
Animals	4.5 (1.3)	2.5	8.0			
Manure	1.2 (3.2)	0.0	12.0			
Changes in stocks						
Soil N	-8.8 (11.9)	-26.8	26.3			
Other stocks	0.0	0.0	0.0			

^a constant value (see Section 2.3 for detail); n/a: not applicable; Inorg., inorganic; BNF: biological N fixation; Atm., atmospheric.

Milk, crops, and animals equaled 48, 45 and 8% of net N outputs, respectively. All farms but three (92%) sold more low-protein crops than the low-protein feed they bought, resulting in a net N output of low-protein crops. On the other hand, the net N input of high-protein feed was positive in all farms. The distinction between high- and low-protein feed and crops clearly showed that the surveyed farms, though growing alfalfa and grass-clover leys, still depended on imported high-protein feeds. They produced nearly all of their forage, and most sold large amounts of low-protein crops such as cereals. Six farms exported cattle manure, but five of them imported other organic fertilizers, mostly pig slurry or chicken manure.

Net indirect N losses due to production and transport of inputs represented 11.4 kg N ha AA⁻¹ (5% of total inputs). Indirect N losses due to high-protein feeds were by far the largest at the farm level, generating 9.7 kg N ha AA⁻¹, equivalent to 26% of the N input of high-protein feed. Indirect N losses from seed production, although small, were greater than the N content of seeds. Finally, the mean change in soil N stock predicted by AMG was -8.8 kg N ha AA⁻¹; it increased for seven farms and decreased > 20 kg N ha AA⁻¹ for eight farms. For five farms (including the four organic farms), the decrease in soil N stock represented > 10% of their total N inputs. The mean decrease in soil N stock for the 38 farms was very close to the median decrease in the same cantons over the last 20 years (GIS Sol, 2013).

3.3. From calculation of NUE to SyNE

The mean NUE of the 38 surveyed farms was 0.39 (range = 0.24-0.69; Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..6). These results are in line with values from the literature (Hristov et al., 2006; Powell et al., 2010; Simon et al., 2000), but higher than studies about specialized dairy farms (Gourley et al., 2012; Nevens et al., 2006; Simon et al., 2000).

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..6. Contribution of each modification of the indicators N use efficiency (NUE) to system N efficiency (SyNE), and farm-gate balance (FGB) to system N balance (SyNB), to mean changes in the indicators for 38 mixed dairy-crop farms surveyed in Brittany, France

	Mean (SD)	Minimum	Maximum	Mean change
NUE	0.39 (0.10)	0.24	0.69	
with net indirect N losses	0.36 (0.09)	0.22	0.65	-5%
with net N inputs/outputs	0.36 (0.09)	0.20	0.65	-6%
with manure as input	0.38 (0.10)	0.19	0.69	-1%
with change in soil N	0.37 (0.10)	0.21	0.65	-4%
SyNE	0.33 (0.09)	0.18	0.58	-15%
FGB	122 (31)	58	202	
with change in soil N	131 (30)	55	191	+7%
with net indirect N losses	133 (34)	68	214	+9%
SyNB	142 (34)	69	238	+17%

Efficiency indicators are unitless; balances in kg N ha agricultural area; SD: standard deviation

Table Erreur ! **Il n'y a pas de texte répondant à ce style dans ce document.**.6 shows the results of including, step-by-step, the conceptual improvements that transform NUE into SyNE. Considering indirect N losses from production and transport of inputs resulted in a decrease in N efficiency for all farms (mean = 5%). Differences were visible between farms that bought processed feed and those that bought simpler crop-based feed. For example, after including indirect N losses of feed production, the NUE of 0.29 and 0.27 for farms F10 and F14 resulted in N use efficiencies of 0.28 (soybean meal) and 0.22 (concentrate compound), respectively.

Calculating net input and net output resulted in a mean 6% decrease in N efficiency (Table Erreur ! **Il n'y a pas de texte répondant à ce style dans ce document.**.6). Many farms bought feed inputs and sold similar crop output, artificially increasing their NUE compared to farms producing their own concentrate. For example, since farm F17 did not sell high-protein crops, its N efficiency did not change when net input/output was taken into account (NUE and N net efficiency = 0.55). In contrast, because farm F11 bought and sold large amounts of high-protein feed, its NUE decreased from 0.55 to an N efficiency of 0.45.

Considering only end products as outputs (*i.e.* manure considered only as an input) decreased N efficiency by 1%. The N use efficiencies of the six farms that exported manure decreased, including that of the one farm (F6) that exported more manure than it imported (from 0.28 to 0.20).

Accounting for a change in soil N stock increased N efficiency for seven farms, in which crop rotations increased soil N stocks. Mean N efficiency of the 38 farms, however, was 4% lower than NUE. When considering a change in soil N stock, the NUE of 0.46 and 0.44 for farms F27 and F35 changed to N use efficiencies of 0.48 and 0.40, respectively.

SyNE is the result of these four modifications in calculating N efficiency. Mean SyNE of the 38 surveyed farms was 0.33 (range = 0.18-0.58) (Table Erreur ! **Il n'y a pas de texte répondant à ce style dans ce document.**.6), 15% lower than mean NUE. Farms F24 and F35 illustrate the irregular relation between NUE and SyNE (Figure Erreur ! **Il n'y a pas de texte répondant à ce style dans ce document.**.4). Farm F24, which bought soybean meal, sold wheat, did not export manure, and had a slight increase in soil N stock, had a NUE of 0.40 decrease to a SyNE of 0.38. In contrast, farm F35, which had high indirect N losses due to large purchases of concentrate compounds and a large decrease in soil N stock, had a NUE of 0.44 decrease to a SyNE of 0.33.

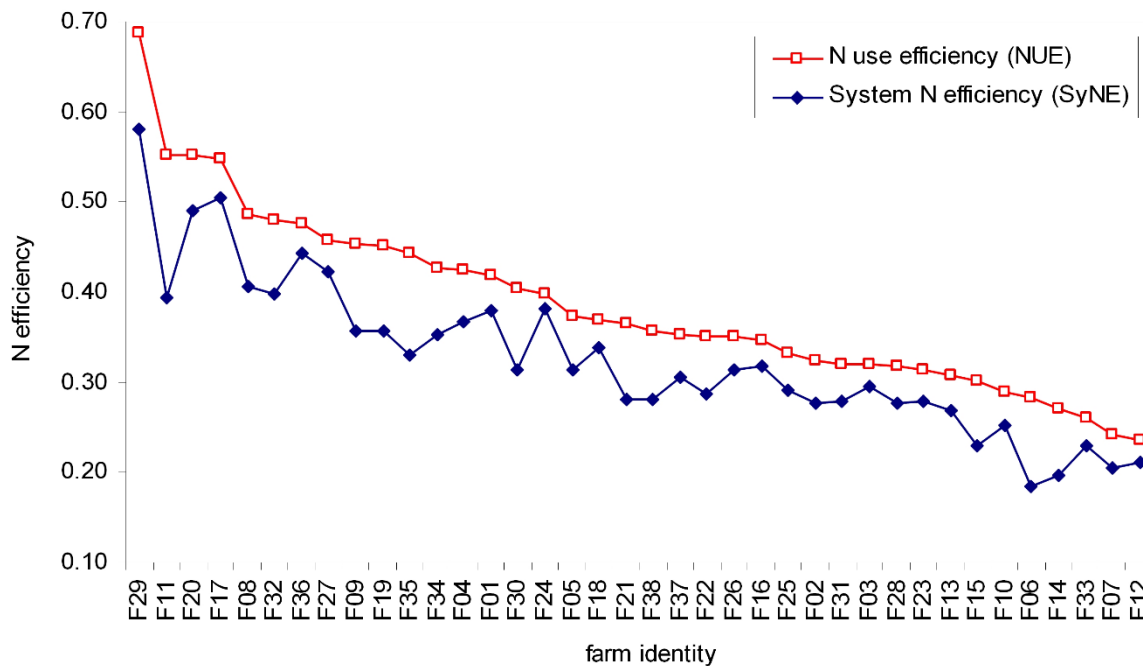


Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..4. **Comparison of NUE and SyNE for 38 mixed dairy-crop farms in Brittany, France**
Farms are ranked by decreasing NUE.

Similarly, SyNB, which included net indirect N losses and change in soil N stock, was higher than FGB for all farms but two (mean = 142 kg N ha AA⁻¹, 17% higher) (Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..6). Net indirect losses represented 9% of SyNB and were the largest source of increase from FGB to SyNB.

3.4. Relation between SyNE and SyNB

Ondersteijn et al. (2002) showed a mathematical link between NUE and FGB, which is also true for SyNE and SyNB. Using equations 3 and 4, SyNE can be expressed as a function of SyNB and either N input or output, which shows the non-linear relation between SyNE and SyNB (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..5). The 38 surveyed farms produced a mean net N output of 68 kg N ha⁻¹ (range = 28-109 kg N ha⁻¹).

4. Discussion

4.1. Changing the meaning of N efficiency

NUE expresses the efficiency of a farm in using N inputs to produce outputs, regardless of their status. Under this definition, manure does not differ from other products; it can be controlled and exported. Moreover, NUE does not consider soil N variations. It therefore does not consider all sources and sinks of N in the farming system. In contrast, SyNE is intended to estimate the ability of a farming system to convert all N inputs into end products for humans, which explains why SyNE is 15% lower than NUE. Similarly, SyNB does not represent local pollution potential, but the pollution potential of the whole farming system, including its inputs production. This

more integrated approach is similar to the calculation of the N footprint (Chatzimpiros and Barles, 2013; Leach et al., 2012).

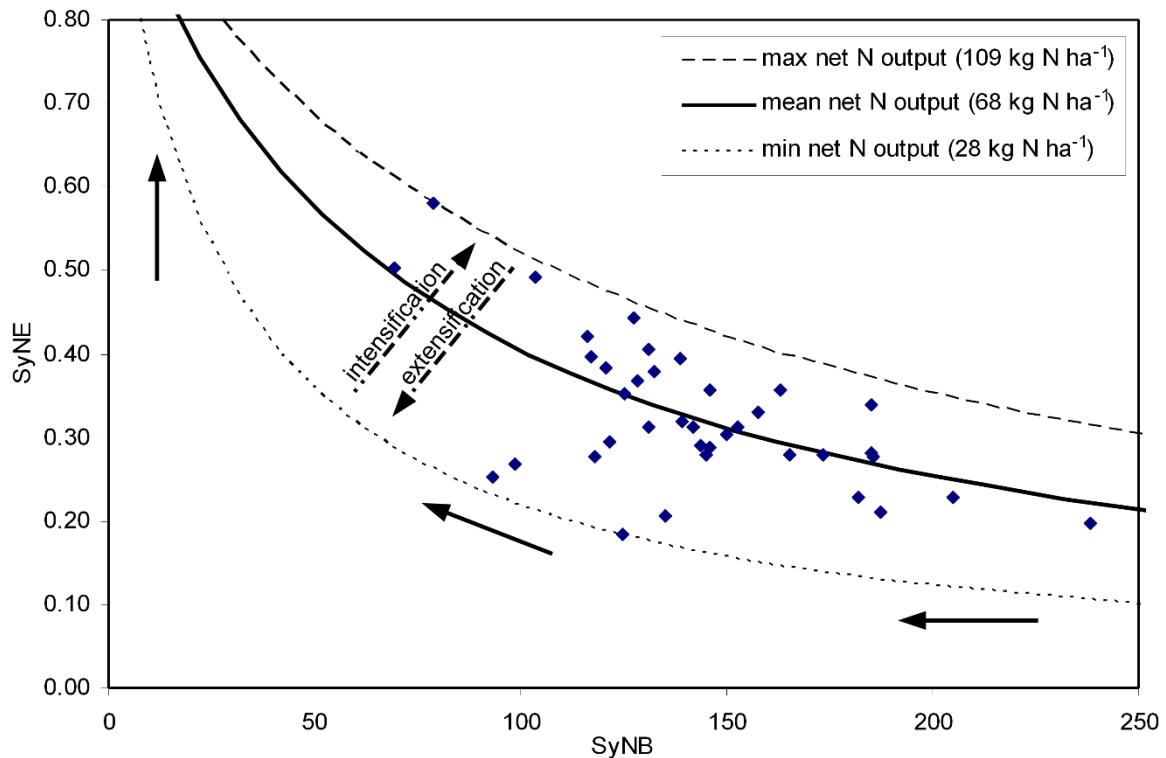


Figure 5. Relationship between SyNE (unitless) and SyNB (kg N ha^{-1}) for 38 mixed dairy-crop farms in Brittany, France
 Curves represent isolines of constant maximum, minimum and mean net N output. Dashed arrows show ineffective strategies to increase SyNE (intensification) or reduce SyNB (extensification). Solid arrows show more sensible strategies to increase SyNE and/or reduce SyNB.

4.2. Benefits of SyNE

Our paper illustrated that SyNE is an improvement of NUE:

- Enlarging the perimeter to include input production and transport gives a more precise estimation of global N efficiency and losses. It also helps to take into account pollution transfers that can occur when externalizing the production of inputs such as feed or replacement animals.
- Calculating net inputs and net outputs corrects an important mathematical bias in NUE. This allows more relevant comparisons between externally dependent and more autonomous farming systems, as well as between mixed and specialized farming systems.
- Revising the definition of outputs to exclude manure better expresses the efficiency of a farming system in transforming inputs into end products.
- Sensitivity analysis showed that calculating change in soil N stock is necessary to account for soil N mining or storage, as it is the most influential variable on SyNE variance. It also gives a more precise estimate of the potential to lose N from the farming system, when included in SyNB calculation.

SyNE was tested on mixed farms to ensure its generality; these complex farms associate animal and crop production, and have a wide diversity of inputs. The indicator developed should therefore be usable for all types of farms, with or without livestock.

4.3. Methodological issues and limits of SyNE

4.3.1. Estimation of change in soil N stock

The change in soil N stock was predicted with a simple model. It was used mainly to demonstrate the importance of systematically considering this major component of the N cycle when evaluating efficiency. The sensitivity analysis, based on a much wider range of change in soil N stock than that of the 38-farm sample, showed that change in soil N stock is the variable that most influences SyNE, illustrating the need to take it into account.

In addition, initial SOM content was the main parameter that influenced model predictions of change in soil N stock (data not shown). Therefore, farms with initially high SOM contents often had decreasing soil N stocks, and farms with low initial SOM contents were more likely to have increasing soil N stocks. Although this is consistent with observed dynamics of SOM (Kätterer and Andrén, 1999; Lemercier et al., 2006), it means that this variable cannot be used for a straightforward comparison of SOM management between farms in different locations. SOM dynamics are complex multifactor phenomena. Only few parameters were considered in this model (*e.g.* soil structure, tillage, precipitation and drainage were ignored). Although its predictions agreed with trends observed in the region (Lemercier et al., 2006), they present a high uncertainty.

Many tools are used to assess SOM dynamics, from physical measures to local references or the use of models. The model that was used in this paper was chosen for its moderate data requirement. However, depending on the available information and context, other tools could be used. Therefore, the international comparisons of SyNE results will need to consider this possible methodological discrepancy.

4.3.2. Status of outputs

We defined manure as a byproduct of animal production and not as an end product since humans cannot use it directly (it was considered as a fertilizer and subtracted from inputs). Still, when used to produce biogas, manure generates an end product (energy) and should therefore be considered as an output, similar to energy crops.

Regarding forage crops, Sutton et al. (2013) argue that they are not an end product used by humans but an intermediate product intended to produce meat and milk. Nevertheless, we decided not to distinguish forage crops from other crops, because production of both manure (for biogas) and forage crops (for animal production) raise the question of the use of outputs. A large fraction of wheat, maize, and barley are transformed into animal feed and therefore comparable to forages not directly used by humans. It is therefore of crucial importance to define the goal of SyNE to make pertinent choices about the outputs considered. In our paper, intended products were considered end products: forage is an intended product, whereas manure is a by-product of meat and milk production.

4.3.3. Farming system perimeter

The indirect N losses considered in this study were expressed per ha of AA of the farm that received the inputs. In LCA, however, impacts per ha usually include the external area, both agricultural and industrial, on which inputs were produced (Basset-Mens and van der Werf, 2005; Cederberg and Mattsson, 2000). We chose to express N losses only per ha of AA of the farm receiving the inputs since it was a more straightforward unit to compare the intensity of N fluxes in mixed dairy and crop farming systems. This choice had no impact on NUE and SyNE since they are unitless, but it had an effect on SyNB, overestimating local N losses because the indirect N losses happened elsewhere. Expressing SyNB per ha of area inside and outside the farm would have “diluted” local N losses over the external area that did not receive the local inputs. In the same manner, it would have been necessary to consider the external area needed for manure spreading for the six farms exporting manure. It is important, however, to keep in mind that indirect N losses represented on average 9% of SyNB for the 38 farms surveyed. Expressing N fluxes per unit of product could be a better option in soil-less farming systems or systems with only one output.

4.3.4. Representativeness of farm sample

As seen in the sensitivity analysis (see Section 3.1.), some variables had a high uncorrelated contribution to variance but a smaller total contribution, due to a negative correlated contribution. It is possible that with other farming systems and practices, correlations would change, making these variables much more influential. Fertilizer and manure input in particular could play a much more influential role in other farming systems.

Manure export was very uncommon in our sample, only occurring in six farms. This is due to the relatively moderate stocking of dairy cattle in Brittany and the high percentage of grazed grass in the forage area, leading to manure amounts that farmers can easily handle on their own AA. In other livestock systems such as concentrated animal feeding operations, this modification of N efficiency is likely to have much larger impacts. Spears et al. (2003) reported that manure output can reach 43% of total N output in large dairy farms in the USA.

4.3.5. Increased data requirements and uncertainty issues

The main limitation of SyNE compared to NUE is its greater need for data. It needs not only N values for inputs and outputs but also LCA references to estimate indirect production losses. We proposed some LCA references in Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..1. These data are rather conservative. It is thus very unlikely that they resulted in an overestimation of N losses due to input production. Uncertainty of LCA data could not be estimated. However, the use of conservative LCA values guarantees that even with a high uncertainty, including input production losses improved the indicator compared to ignoring them.

Data for soil N dynamics estimation vary depending on the method. The soil model we used required soil and temperature data available from farmers or public databases. These data, as well as the model itself, increased the uncertainty of the efficiency indicator. We suggest that the use of a less biased efficiency indicator justifies this additional data collection and increased

uncertainty. However, this highlights the need to quantify the uncertainty of soil model predictions and to estimate the overall uncertainty of the SyNE indicator. This would also be necessary for NUE, as important uncertainty issues are associated with the estimation of some variables such as biological N fixation.

4.4. Combining SyNE and SyNB for better N management

Nevens et al. (2006) chose to express eco-efficiency as the output:NS ratio. Eco-efficiency and SyNE are related indicators, the former expressing products as a function of N surplus and the latter as a function of inputs. We thought it more relevant to relate output to input, since this concept was more tangible for farmers. Ondersteijn et al. (2003) have shown that environmental impacts of dairy farms in the Netherlands are not strongly related to farmer strategies but to financial performance. SyNE thus seems more operational than eco-efficiency to evaluate modifications of farming systems on N efficiency.

We therefore developed complementary indicators: SyNE expressing the ability of a farming system to transform N inputs into end products and SyNB reflecting the potential for total N losses from the farming system. For a given net output, increasing SyNE reduces SyNB (Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..5**); however, this relation does not hold when productivity changes. It is possible to increase SyNE and SyNB simultaneously by intensifying production per ha or decreasing them simultaneously by decreasing production per ha (dotted arrows, Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..5**). More sensible strategies to improve N management depend on the initial situation (solid arrows, Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document..5**). For an objective of productive and cleaner agriculture, it seems straightforward that farmers with high SyNB should focus on reducing it. In contrast, farmers with low SyNB and SyNE could work on increasing productivity. The combination of SyNE and SyNB is particularly useful for evaluating the strategies of farmers with average efficiencies and output, since they have to find ways to reduce SyNB without decreasing output. Therefore, using these two complementary indicators can help balance production and environmental impacts, which is one of the main challenges of today's agriculture (Foley et al., 2011).

5. Conclusion

SyNE offers some important improvements to the existing N efficiency indicator, NUE. It gives sound information about the ability of a farming system to transform inputs into end outputs for human consumption. However, its calculation requires a larger amount of data than NUE, and modeling is necessary to estimate change in soil N in absence of local references. Soil N change is also the most influential variable on SyNE in our 38 dairy farms sample. Uncertainty analysis could give a useful insight in which variables need to be estimated with more confidence.

Combined with SyNB, SyNE should help in evaluating efficiency-improvement scenarios that reduce potential N losses. It could therefore be a useful tool to help produce more food with less pollution, which is one of the main challenges of modern agriculture.

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References

- Aarts, H.F.M., Biewinga, E.E., van Keulen, H., 1992. Dairy farming systems based on efficient nutrient management. *Neth. J. Agric. Sci.* 40, 285–299.
- Aarts, H.F.M., Habekotté, B., Van Keulen, H., 2000. Nitrogen (N) management in the ‘De Marke’ dairy farming system. *Nutr. Cycl. Agroecosystems* 56, 231–240. <https://doi.org/10.1023/A:1009885419512>
- Agreste, 2010. *Pratiques culturales 2006* (No. 8), Les Dossiers.
- Andriulo, A., Mary, B., Guerif, J., 1999. Modelling soil carbon dynamics with various cropping sequences on the rolling pampas. *Agronomie* 19, 365–377. <https://doi.org/10.1051/agro:19990504>
- Bassanino, M., Grignani, C., Sacco, D., Allisiardi, E., 2007. Nitrogen balances at the crop and farm-gate scale in livestock farms in Italy. *Agric. Ecosyst. Environ.* 122, 282–294. <https://doi.org/10.1016/j.agee.2007.01.023>
- Basset-Mens, C., van der Werf, H.M.G., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. *Agric. Ecosyst. Environ.* 105, 127–144. <https://doi.org/10.1016/j.agee.2004.05.007>
- Bleken, M.A., Steinshamn, H., Hansen, S., 2005. High Nitrogen Costs of Dairy Production in Europe: Worsened by Intensification. *Ambio* 34, 598–606. <https://doi.org/10.1579/0044-7447-34.8.598>
- Boiffin, J., KéLi Zagbahi, J., Sebillotte, M., 1986. Systèmes de culture et statut organique des sols dans le Noyonnais: application du modèle de Hénin-Dupuis. *Agronomie* 6, 437–446. <https://doi.org/10.1051/agro:19860503>
- Bordet, A.C., Bochu, J.L., Trevisiol, A., 2010. *Références PLANETE 2010, Fiche 4 - Production “Bovins lait et cultures.”* Solagro, Toulouse, France.
- Cederberg, C., Mattsson, B., 2000. Life cycle assessment of milk production - a comparison of conventional and organic farming. *J. Clean. Prod.* 8, 49–60. [https://doi.org/10.1016/S0959-6526\(99\)00311-X](https://doi.org/10.1016/S0959-6526(99)00311-X)
- Chatzimpiros, P., Barles, S., 2013. Nitrogen food-print: N use related to meat and dairy consumption in France. *Biogeosciences* 10, 471–481. <https://doi.org/10.5194/bg-10-471-2013>
- CORPEN, 1988. *Bilan de l’azote à l’exploitation.* Ministère de l’Agriculture et de la Forêt, Paris, France.

- Dalgaard, T., Bienkowski, J.F., Bleeker, A., Drouet, J.L., Durand, P., Dragosits, U., Frumau, A., Hutchings, N.J., Kedziora, A., Magliulo, V., Olesen, J.E., Theobald, M.R., Maury, O., Akkal, N., Cellier, P., 2012. Farm nitrogen balances in six European agricultural landscapes, a method for farming system assessment, emission hotspot identification, and mitigation measure evaluation. *Biogeosciences Discuss.* 9, 8859–8904. <https://doi.org/10.5194/bgd-9-8859-2012>
- DRAAF Bretagne, 2011. *Statistique agricole annuelle 2010 (No. 25)*, Agreste Bretagne. Rennes (France).
- FAO, 2014. FAOSTAT [WWW Document]. Stat. Database. URL <http://faostat3.fao.org/> (accessed 2.5.14).
- FAO, 2010. *Greenhouse gas Emissions from the Dairy Sector: A Life Cycle Assessment (No. K7930E)*. FAO, Rome (Italy).
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O’Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342. <https://doi.org/10.1038/nature10452>
- Fresco, L.O., Westphal, E., 1988. A hierarchical classification of farm systems. *Exp. Agric.* 24, 399–419.
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 320, 889–892. <https://doi.org/10.1126/science.1136674>
- GIS Sol, 2013. *Base de Données Analyses de Terre* [WWW Document]. URL <http://bdat.gissol.fr/> (accessed 2.20.13).
- Gourley, C.J.P., Dougherty, W.J., Weaver, D.M., Aarons, S.R., Awty, I.M., Gibson, D.M., Hannah, M.C., Smith, A.P., Peverill, K.I., 2012. Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms. *Anim. Prod. Sci.* 52, 929. <https://doi.org/10.1071/AN11337>
- Halberg, N., 1999. Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farmers. *Agric. Ecosyst. Environ.* 76, 17–30. [https://doi.org/10.1016/S0167-8809\(99\)00055-9](https://doi.org/10.1016/S0167-8809(99)00055-9)
- Halberg, N., Steen Kristensen, E., Sillebak Kristensen, I., 1995. Nitrogen turnover on organic and conventional mixed farms. *J. Agric. Environ. Ethics* 8, 30–51. <https://doi.org/10.1007/BF02286400>
- Helton, J.C., Davis, F.J., 2003. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. *Reliab. Eng. Syst. Saf.* 81, 23–69. [https://doi.org/10.1016/S0951-8320\(03\)00058-9](https://doi.org/10.1016/S0951-8320(03)00058-9)
- Hristov, A.N., Hazen, W., Ellsworth, J.W., 2006. Efficiency of Use of Imported Nitrogen, Phosphorus, and Potassium and Potential for Reducing Phosphorus Imports on Idaho Dairy Farms. *J. Dairy Sci.* 89, 3702–3712. [https://doi.org/10.3168/jds.S0022-0302\(06\)72411-0](https://doi.org/10.3168/jds.S0022-0302(06)72411-0)

- INRA, CIRAD, AFZ, FAO, 2013. Feedipedia - Animal Feed Resources Information System [WWW Document]. URL <http://www.feedipedia.org/> (accessed 7.24.13).
- Jarvis, S., 2001. Improving nitrogen use efficiency from balance sheets: opportunities to reduce losses?, in: *Element Balances as a Sustainability Tool: Workshop in Uppsala on March 16–17, 2001*, JTI-Rapport Lantbruk & Industri 281. Presented at the Element balances as a sustainability tool Workshop, Swedish Institute of Agricultural and Environmental Engineering, Uppsala (Sweden), p. 25.
- Kätterer, T., Andrén, O., 1999. Long-term agricultural field experiments in Northern Europe: analysis of the influence of management on soil carbon stocks using the ICBM model. *Agric. Ecosyst. Environ.* 72, 165–179. [https://doi.org/10.1016/S0167-8809\(98\)00177-7](https://doi.org/10.1016/S0167-8809(98)00177-7)
- Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. *Environ. Dev.* 1, 40–66. <https://doi.org/10.1016/j.envdev.2011.12.005>
- Leip, A., Britz, W., Weiss, F., de Vries, W., 2011. Farm, land, and soil nitrogen budgets for agriculture in Europe calculated with CAPRI. *Environ. Pollut.* 159, 3243–3253. <https://doi.org/10.1016/j.envpol.2011.01.040>
- Lemercier, B., Walter, C., Schwartz, C., Saby, N.P.A., Arrouays, D., Follain, S., 2006. Suivi des teneurs en carbone organique et en phosphore extractible dans les sols agricoles de trois régions françaises. *Etude Gest. Sols* 13, 165–180.
- Mahieu, S., Germon, F., Aveline, A., Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2009. The influence of water stress on biomass and N accumulation, N partitioning between above and below ground parts and on N rhizodeposition during reproductive growth of pea (*Pisum sativum* L.). *Soil Biol. Biochem.* 41, 380–387. <https://doi.org/10.1016/j.soilbio.2008.11.021>
- Monti, A., Di Virgilio, N., Venturi, G., 2008. Mineral composition and ash content of six major energy crops. *Biomass Bioenergy* 32, 216–223. <https://doi.org/10.1016/j.biombioe.2007.09.012>
- Nemecek, T., Kägi, T., 2007. Life cycle inventories of agricultural production systems, data v2.0 (No. 15), Ecoinvent report. Ecoinvent Center, Zürich and Dübendorf (Switzerland).
- Nevens, F., Verbruggen, I., Reheul, D., Hofman, G., 2006. Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: Evolution and future goals. *Agric. Syst.* 88, 142–155. <https://doi.org/10.1016/j.agsy.2005.03.005>
- Nguyen, C., 2003. Rhizodeposition of organic C by plants: mechanisms and controls. *Agronomie* 23, 375–396. <https://doi.org/10.1051/agro:2003011>
- OECD, EUROSTAT, 2007. *Gross Nitrogen Balances Handbook*.
- Ondersteijn, C.J.M., Beldman, A.C.G., Daatselaar, C.H.G., Giesen, G.W.J., Huirne, R.B.M., 2002. The Dutch Mineral Accounting System and the European Nitrate Directive: implications for N and P management and farm performance. *Agric. Ecosyst. Environ.* 92, 283–296. [https://doi.org/10.1016/S0167-8809\(01\)00288-2](https://doi.org/10.1016/S0167-8809(01)00288-2)
- Ondersteijn, C.J.M., Giesen, G.W.J., Huirne, R.B.M., 2003. Identification of farmer characteristics and farm strategies explaining changes in environmental management and

- environmental and economic performance of dairy farms. *Agric. Syst.* 78, 31–55. [https://doi.org/10.1016/S0308-521X\(03\)00031-3](https://doi.org/10.1016/S0308-521X(03)00031-3)
- Oomen, G.J.M., Lantinga, E.A., Goewie, E.A., Van der Hoek, K.W., 1998. Mixed farming systems as a way towards a more efficient use of nitrogen in European Union agriculture. *Environ. Pollut.* 102, 697–704. [https://doi.org/10.1016/S0269-7491\(98\)80101-2](https://doi.org/10.1016/S0269-7491(98)80101-2)
- Powell, J.M., Gourley, C.J.P., Rotz, C.A., Weaver, D.M., 2010. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environ. Sci. Policy* 13, 217–228. <https://doi.org/10.1016/j.envsci.2010.03.007>
- R Core Team, 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rasmussen, J., Sørensen, K., Pirhofer-Walzl, K., Eriksen, J., 2012. N₂-fixation and residual N effect of four legume species and four companion grass species. *Eur. J. Agron.* 36, 66–74. <https://doi.org/10.1016/j.eja.2011.09.003>
- Rouillé, B., Brunschwig, P., Le Gall, A., 2008. Evaluation des consommations globales de concentrés par les vaches laitières et disponibilités possibles en coproduits d'agrocarburants (No. 140831027), Résultats. Institut de l'Élevage, CNIEL, Paris (France).
- Ruiz, L., Abiven, S., Durand, P., Martin, C., Vertès, F., Beaujouan, V., 2002. Effect on nitrate concentration in stream water of agricultural practices in small catchments in Brittany: I. Annual nitrogen budgets. *Hydrol. Earth Syst. Sci.* 6, 497–506. <https://doi.org/10.5194/hess-6-497-2002>
- Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil organic carbon. *Soil Biol. Biochem.* 40, 594–607. <https://doi.org/10.1016/j.soilbio.2007.08.022>
- Schröder, J.J., Aarts, H.F.M., ten Berge, H.F.M., van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. *Eur. J. Agron.* 20, 33–44. [https://doi.org/10.1016/S1161-0301\(03\)00070-4](https://doi.org/10.1016/S1161-0301(03)00070-4)
- Schröder, J.J., Neeteson, J.J., 2008. Nutrient management regulations in The Netherlands. *Geoderma* 144, 418–425. <https://doi.org/10.1016/j.geoderma.2007.12.012>
- Simon, J.-C., Grignani, C., Jacquet, A., Corre, L.L., Pagès, J., 2000. Typologie des bilans d'azote de divers types d'exploitation agricole: recherche d'indicateurs de fonctionnement. *Agronomie* 20, 175–195. <https://doi.org/10.1051/agro:2000118>
- Smil, V., 2002. Nitrogen and Food Production: Proteins for Human Diets. *Ambio* 31, 126–131. [https://doi.org/10.1639/0044-7447\(2002\)031\[0126:NAFPPF\]2.0.CO;2](https://doi.org/10.1639/0044-7447(2002)031[0126:NAFPPF]2.0.CO;2)
- Smil, V., 1999. Nitrogen in crop production: An account of global flows. *Glob. Biogeochem. Cycles* 13, 647–662. [https://doi.org/199910.1029/1999GB900015](https://doi.org/10.1029/1999GB900015)
- Spears, R.A., Kohn, R.A., Young, A.J., 2003. Whole-Farm Nitrogen Balance on Western Dairy Farms. *J. Dairy Sci.* 86, 4178–4186. [https://doi.org/10.3168/jds.S0022-0302\(03\)74033-8](https://doi.org/10.3168/jds.S0022-0302(03)74033-8)
- Spriensma, R., 2004. SimaPro database manual: the BUWAL 250 library. PRé Consult. Amersfoort Neth.
- Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz,

- R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S., 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Centre for Ecology and Hydrology.
- Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B., 2011. The European nitrogen assessment: sources, effects, and policy perspectives. Cambridge University Press, Cambridge (UK).
- Sutton, M.A., Reis, S. (Eds.), 2011. The nitrogen cycle and its influence on the European greenhouse gas balance. Centre for Ecology & Hydrology, Wallingford (UK).
- Thiébeau, P., Larbre, D., Usunier, J., Cattin, G., Parnaudeau, V., Justes, E., 2004. Effets d'apports de lisier de porcs sur la production d'une luzerne et la dynamique de l'azote du sol. *Fourrages* 511–525.
- Tirard, S., 2011. Bilans des Minéraux du Réseau Lait en Bretagne. *Cap Elev.* 4–5.
- UMR 1069 SAS, Unpublished results. Life cycle inventory data from French agricultural productions. INRA, Rennes (France).
- UNECE, 2012. Draft decision on adoption of guidance document on preventing and abating ammonia emissions from agricultural sources (No. ECE/EB.AIR/2012/L.9). Economic Commission for Europe - Executive Body for the Convention on Long-range Transboundary Air Pollution, Geneva (Switzerland).
- Vellinga, Th.V., Bannink, A., Smits, M.C.J., Van den Pol-Van Dasselaar, A., Pinxterhuis, I., 2011. Intensive dairy production systems in an urban landscape, the Dutch situation. *Livest. Sci.* 139, 122–134. <https://doi.org/10.1016/j.livsci.2011.03.010>
- Vertès, F., Hatch, D., Velthof, G., Taube, F., Laurent, F., Loiseau, P., Recous, S., 2007. Short-term and cumulative effects of grassland cultivation on nitrogen and carbon cycling in ley-arable rotations, in: *Grassland Science in Europe, Grassland Science in Europe. Presented at the Permanent and temporary grassland: plant, environment and economy, European Grassland Federation, Ghent, Belgium*, pp. 227–246.
- Vertès, F., Mary, B., 2007. Modelling the long term SOM dynamics in fodder rotations with a variable part of grassland. Presented at the International Symposium on Organic Matter Dynamics in Agro-Ecosystems, Poitiers (France), pp. 549–550.
- Vertès, F., Simon, J., 1991. Pourquoi et comment estimer le pourcentage de trèfle dans les associations graminée-légumineuse. *Fourrages* 127, 297–312.
- Watson, C., Atkinson, D., 1999. Using nitrogen budgets to indicate nitrogen use efficiency and losses from whole farm systems: a comparison of three methodological approaches. *Nutr. Cycl. Agroecosystems* 53, 259–267.
- Watson, C.A., Bengtsson, H., Ebbesvik, M., Løes, A., Myrbeck, A., Salomon, E., Schroder, J., Stockdale, E.A., 2002. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. *Soil Use Manag.* 18, 264–273. <https://doi.org/10.1111/j.1475-2743.2002.tb00268.x>
- Wilkins, R.J., 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 517–525. <https://doi.org/10.1098/rstb.2007.2167>

Xu, C., Gertner, G.Z., 2008. Uncertainty and sensitivity analysis for models with correlated parameters. *Reliab. Eng. Syst. Saf.* 93, 1563–1573.
<https://doi.org/10.1016/j.ress.2007.06.003>