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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

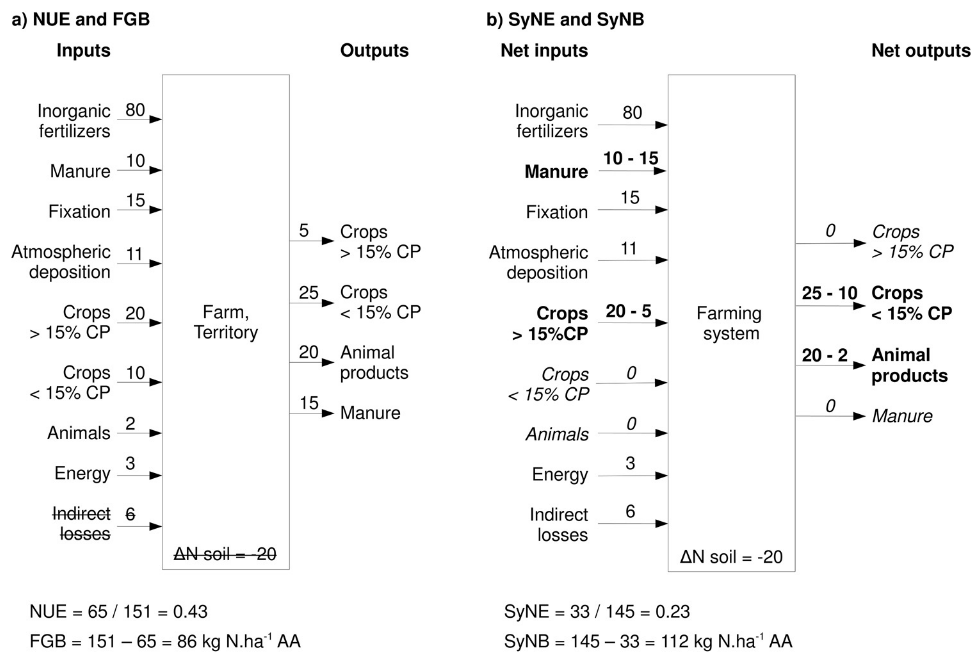

Fig. 1. Sample calculation of four nitrogen management indicators at farm and territory scales: nitrogen use efficiency (NUE), farm-gate balance (FGB), system nitrogen efficiency (SyNE) and system nitrogen balance (SyNB). All flows in kg N ha^{-1} AA. Data do not represent real farming systems. Terms crossed out are excluded from the calculation of NUE and FGB. Terms in italics are subtracted from the corresponding terms in bold to calculate net flows. CP: crude protein; ΔN soil: annual soil N change; AA: agricultural area.

were not available; therefore, it was excluded from analysis. Land use data come from the statistical service of the United Nations Food and Agriculture Organization (FAO, 2014). They include arable land, permanent grasslands and permanent crops. Agricultural Area (AA) is defined as the sum of these three components. Only agricultural activity was studied; so, boundaries exclude N flows from marine fisheries, aquaculture and forestry.

2.2.1. Nitrogen inputs

The FAO database (FAO, 2014) provided import data for 77 crops at the national scale, expressed in tons of fresh weight. These data were converted into N using N contents from FAO (2014), the Feedipedia database (INRA et al., 2013) and Lassaletta et al. (2014b). Only crop imports used as agricultural inputs (e.g. animal feed, seeds) need to be considered when calculating the nitrogen management indicators. Therefore, total imports for each crop were allocated according to the national uses provided by the FAOSTAT database (FAO, 2014).

Inorganic and organic fertilizer use was provided by EUROSTAT (2014), directly expressed in tons of N.

N deposition was calculated from the European Monitoring and Evaluation Program (EMEP, 2014). It includes deposition from agricultural and non-agricultural sources of oxidized and reduced N on agricultural land, according to the recommendations of EUROSTAT (2013).

Biological nitrogen fixation (BNF) by legume crops came from the EUROSTAT database (EUROSTAT, 2014). These data include 4 kg N ha^{-1} AA of non-symbiotic fixation by free-living soil bacteria (OECD and EUROSTAT, 2007). However, it is recommended to include non-symbiotic fixation only for arable land (Baddeley et al., 2014; Smil, 1999). We therefore subtracted 4 kg N ha^{-1} from the BNF of permanent grassland and permanent crop areas.

EUROSTAT (2014) provided national data on imports, exports and changes in stocks of manure. Manure imports also included domestic organic fertilizers (sewage sludge, industrial waste) coming from non-agricultural sectors, while manure exports include the domestic use of manure by non-agricultural sectors. Energy consumption (liquid fuel and natural gas) by the agricultural sector also came from the EUROSTAT database (EUROSTAT, 2014) and was converted into N emissions based on life cycle inventories (Godinot et al., 2014).

2.2.2. Nitrogen outputs

We used crop production data from the FAOSTAT database (FAO, 2014). Like for crop imports, fresh weight was converted into N. Crops used by the agricultural sector are considered internal flows and should not be considered when calculating the indicators. Based on national uses from FAO (2014), animal consumption and seed production were subtracted from total production. FAOSTAT data (FAO, 2014) were also used for animal production. Net national animal production was available in FAOSTAT as production minus imports of similar animals. The data were converted from carcass weight into N flows using N content information from FAO (2014) and Leip et al. (2011b).

2.2.3. Indirect losses

N losses related to the production and transport of net crop imports and energy were estimated from life cycle inventory data (Godinot et al., 2014). Due to the lack of information about the nature of inorganic fertilizers, indirect losses for their production and transport were estimated at 2% of their N content for all types of fertilizer for all member states.

2.2.4. Annual change in soil organic nitrogen content

The annual change in soil organic N content was estimated from the mean change in soil organic carbon at the European scale (Vleeshouwers and Verhagen, 2002) under annual crops and permanent crops and grasslands. A C:N ratio of 12 (Leip et al., 2008) was used to convert soil organic carbon into soil organic N. This resulted in an annual loss of 70 kg N ha^{-1} AA under annual crops and an annual increase of 43 kg N ha^{-1} AA under permanent crops and grasslands.

2.3. Calculation of net inputs and outputs

Calculating net flows is an essential step for calculating SyNE because it corrects a mathematical bias in NUE when certain inputs and outputs are similar (Godinot et al., 2014).

Crude protein (CP; calculated as N content × 6.25) content is a suitable proxy for the substitution capacity of feed inputs and crop outputs. Two categories of crops and feedstuffs were defined based on CP content: high protein (≥ 15% CP, dry matter basis) and low protein (<15% CP). This classification enabled calculating net inputs and net outputs for only two CP categories (high and low), assuming that crops and feedstuffs within each category were interchangeable. If agricultural production was greater than feed imports in a given CP category, then net outputs were calculated as production minus imports, and net imports were set to zero. However, if feed imports were greater than agricultural production in a given CP category, net imports were calculated as imports minus production, and net production was set to zero (Fig. 1).

Net animal output was directly available from FAOSTAT (FAO, 2014) as national production minus imports of the same animals. No member state imported more live animals than it produced, which resulted in net animal input always equaling zero.

Manure is not a desired output of EU agriculture, unlike crop and animal products. However, it is a highly valuable organic fertilizer. Therefore, manure was always considered an input: manure output was converted into a negative manure input (Godinot et al., 2014). Net manure input was calculated as manure input minus output, which in some cases could result in a negative net input. Net manure output was always set to zero (Fig. 1).

2.4. Statistical analyses

Statistical analyses were performed with R software (R Core Team, 2014). They consisted of simple descriptive statistics such as means, standard deviations and Pearson correlation coefficients.

3. Results and discussion

3.1. National N flows

Fig. 2 and Table 2 present the mean annual N flows for each of the EU-27 member states for the 2000–2008 period. All means calculated in this work are unweighted arithmetic means, in order to compare countries to a collective reference with no effect of size. Mean net animal output was 22 kg N ha^{-1} AA and ranged from 4 to 108 kg N ha^{-1} AA. Mean net crop output was 11 kg N ha^{-1} AA and ranged from 0 to 32 kg N ha^{-1} AA. During this period, 10 member states had net outputs composed of over 60% animal products. This animal orientation was particularly strong in Malta, the Netherlands and Portugal. They had no net crop output during this period because they imported more feed than their national crop production of both high- and low-protein crops. Seven countries had a crop orientation, with net outputs composed of over 60% crops. Bulgaria had the highest percentage of crops in its net output (80%). The 10 other countries had relatively equal net crop and animal outputs.

Production intensity varied greatly (Fig. 2). Five countries had a total net output below 15 kg N ha^{-1} AA (Greece, Portugal, Latvia, Spain and Estonia, in increasing order), while three produced over 60 kg N ha^{-1} AA (Belgium, the Netherlands and Malta, in increasing order).

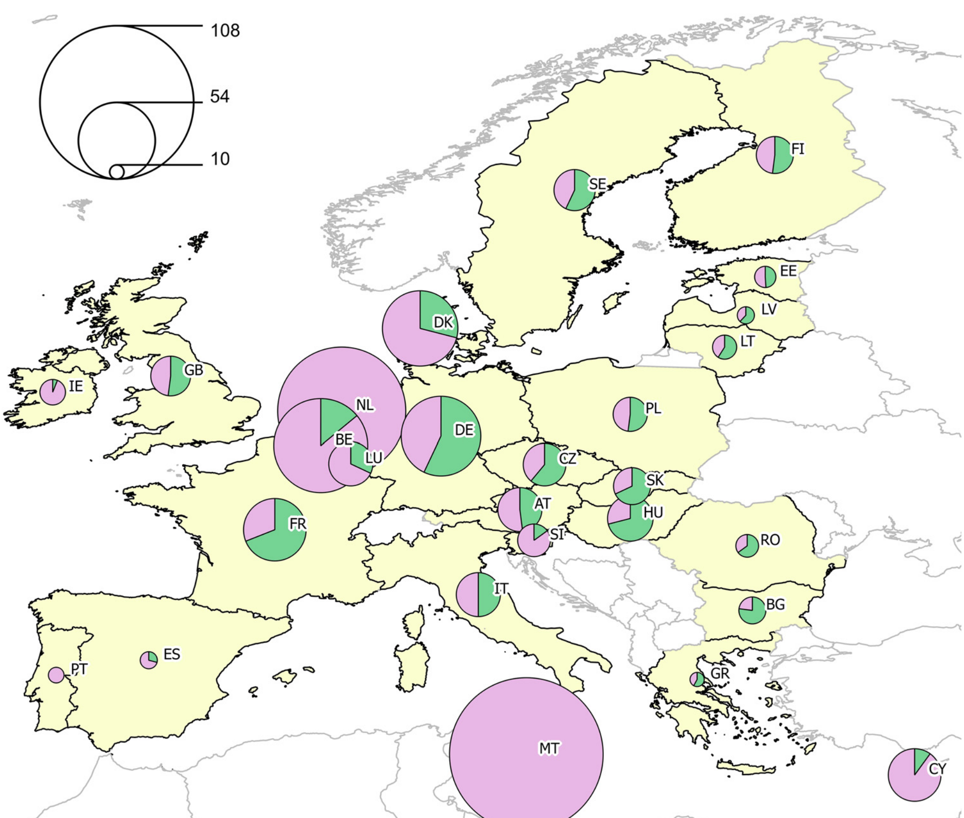

Fig. 2. Nature and intensity of mean annual net N output of EU-27 member states for the 2000–2008 period. The green portion of the pie chart represents the proportion of net crop output, the purple portion the proportion of net animal output. The diameter of the pie chart is proportional to the intensity of total net output (kg N ha^{-1} AA). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Mean annual N inputs and outputs of EU-27 member states for the 2000–2008 period (kg N ha^{-1} AA).

Member State	AA (1000 ha)	Net crop output	Net animal output	Inorganic fertilizer	N deposition	Feed import	Biological N fixation	Indirect N losses	Energy combustion	Organic fertilizer	ΔN soil
Austria	3299	15	16	33	13	10	8	2	2	2	-4
Belgium	1385	9	57	106	18	96	5	22	14	-4	-25
Bulgaria	5300	15	4	30	9	0	5	1	1	0	-26
Cyprus	147	4	33	43	4	77	5	14	6	1	-40
Czech Republic	4263	18	11	70	14	1	13	2	2	2	-42
Denmark	2671	15	37	80	12	52	4	8	4	4	-54
Estonia	874	7	8	29	6	1	9	1	2	0	-30
Finland	2260	13	12	70	3	9	4	2	5	0	-67
France	29553	30	14	79	12	8	14	3	3	1	-27
Germany	16992	32	24	106	17	0	7	2	3	5	-35
Greece	8363	6	4	28	7	2	4	1	3	0	3
Hungary	5841	23	9	49	12	7	5	2	1	-5	-45
Ireland	4323	1	17	83	8	11	1	4	2	1	13
Italy	14859	15	15	51	15	17	16	3	4	1	-16
Latvia	1693	8	5	22	7	1	13	1	1	0	-27
Lithuania	2816	10	7	41	9	1	6	1	0	0	-32
Luxembourg	129	10	21	115	18	9	3	4	4	1	-10
Malta	10	0	108	61	11	307	4	99	0	0	-56
Netherlands	1934	0	90	148	23	177	4	34	8	-7	-15
Poland	16643	12	11	56	13	4	5	2	4	0	-43
Portugal	3788	0	11	33	5	23	2	5	3	1	1
Romania	14321	10	6	18	10	0	8	0	0	0	-28
Slovakia	2094	18	8	39	12	1	12	1	1	3	-32
Slovenia	503	3	20	62	15	15	3	3	4	0	4
Spain	28984	4	9	37	7	14	4	2	2	1	-7
Sweden	3159	16	12	56	4	9	13	3	2	1	-52
United Kingdom	17225	15	14	71	9	9	6	3	1	4	5
Unweighted mean	7164	11	22	60	11	32	7	8	3	0	-25

Countries with light gray shading have over 60% animal products in their net production; countries with dark gray shading have over 60% crop products in their net production. AA: agricultural area; Indirect N losses: indirect losses related to input production and transport; ΔN soil: soil N change

Inorganic fertilizer was the main input in 24 of the 27 member states, representing a mean of 60 kg N ha^{-1} AA. Net feed input (32 kg N ha^{-1} AA) was the second highest input for eight countries, and the highest for Cyprus, the Netherlands and Malta. Atmospheric deposition was generally the third highest input (mean = 11 kg N ha^{-1} AA). It represented more than 15% of total net input in three countries with low total net N inputs: Romania, Greece and Austria. Biological N fixation (mean = 7 kg N ha^{-1} AA) was the fourth highest input. Energy combustion (mean = 3 kg N ha^{-1} AA) was a minor input for most countries. Only the Netherlands and Belgium had emissions related to energy-intensive production systems, such as greenhouses and confined animal production, that were greater than 6 kg N ha^{-1} AA. Net organic fertilizer input was generally close to zero because manure exchanges between countries were relatively small. However, four countries were net exporters of manure: Estonia, Belgium, Hungary and the Netherlands, in increasing order.

Net indirect losses (mean = 8 kg N ha^{-1} AA) were linked mostly to production of imported feed and were higher for major feed importers such as Cyprus, Belgium, the Netherlands and Malta, in increasing order.

Change in soil organic N was a major N source for most countries, with a mean reduction in soil N stock of 25 kg N ha^{-1} AA. Only five countries stored organic N in their soils during the 2000–2008 period: Portugal, Greece, Slovenia, the United Kingdom and Ireland, in increasing order.

Table 3
Mean efficiency indicators (SyNE, RNE, NUE, unitless) and loss indicator (SyNB, kg N ha^{-1} AA) of EU-27 member states for the 2000–2008 period.

Member State	SyNB	SyNE	RNE	NUE
Austria	44	0.42	0.78	0.49
Belgium	216	0.23	0.51	0.38
Bulgaria	52	0.27	0.38	0.45
Cyprus	153	0.19	0.42	0.31
Czech Republic	116	0.20	0.32	0.35
Denmark	164	0.24	0.47	0.39
Estonia	64	0.19	0.35	0.38
Finland	135	0.16	0.29	0.30
France	102	0.30	0.47	0.41
Germany	120	0.32	0.54	0.46
Greece	31	0.26	0.45	0.31
Hungary	85	0.27	0.38	0.48
Ireland	76	0.20	0.56	0.20
Italy	92	0.25	0.45	0.34
Latvia	60	0.17	0.28	0.30
Lithuania	74	0.19	0.32	0.32
Luxembourg	132	0.19	0.46	0.25
Malta	431	0.20	0.44	0.38
Netherlands	312	0.22	0.52	0.32
Poland	104	0.19	0.32	0.32
Portugal	60	0.16	0.37	0.23
Romania	49	0.24	0.39	0.46
Slovakia	75	0.26	0.39	0.43
Slovenia	75	0.24	0.56	0.31
Spain	61	0.17	0.33	0.24
Sweden	111	0.21	0.36	0.36
United Kingdom	69	0.29	0.52	0.32
Unweighted mean	113	0.23	0.43	0.35

Countries with light gray shading have over 60% animal products in their net production; countries with dark gray shading have over 60% crop products in their net production. AA: agricultural area; SyNB: system N balance; SyNE: system N efficiency; RNE: relative N efficiency; NUE: N use efficiency.

3.2. *Utility of the system nitrogen efficiency indicator (SyNE)*

Godinot et al. (2014) demonstrated the utility of the SyNE indicator compared to NUE at the farming system scale. A large difference was observed between these efficiency indicators at the territory scale (Table 3). SyNE varied from 0.16 to 0.42 (mean = 0.23), while NUE varied from 0.20 to 0.49 (mean = 0.35). The value for mean NUE is similar to the efficiency calculated by

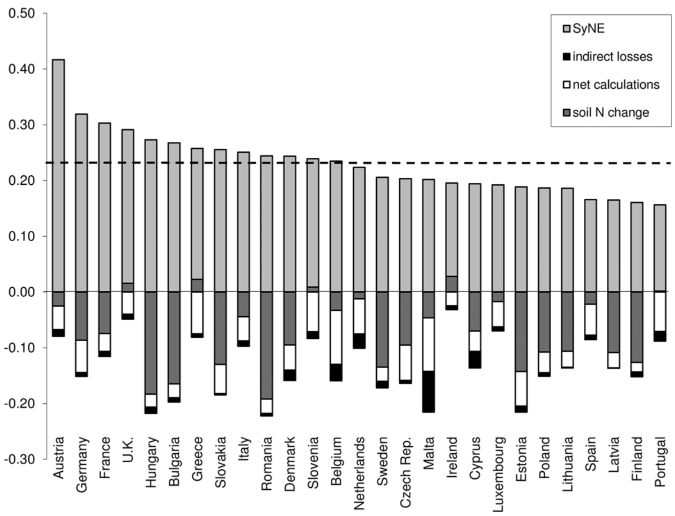

Fig. 3. Nature of differences between system N efficiency (SyNE) and N use efficiency (NUE) of EU-27 member states for the 2000–2008 period. Countries are ranked by decreasing SyNE. The dashed line represents mean SyNE. NUE equals SyNE minus all other bars. This highlights the efficiency variations that are not considered in NUE: soil N change, net calculations of inputs and outputs and indirect losses.

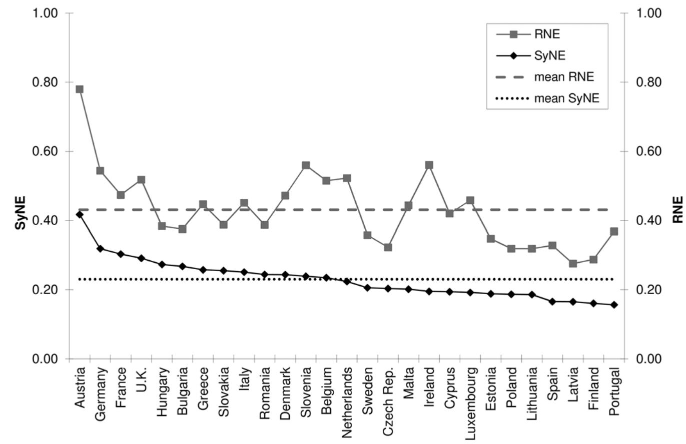

Fig. 4. Comparison of mean system N efficiency (SyNE) and relative N efficiency (RNE) of EU-27 member states for the 2000–2008 period. Countries are ranked by decreasing SyNE.

Van der Hoek (2001) for the EU-15 in 1998 and by Leip et al. (2011b) for EU27 for years 2001–2003.

SyNE and NUE are correlated ($r(25) = 0.72$; $p < 0.001$), but the mean decrease of 34% in SyNE compared to NUE illustrates the exclusion of certain flows in NUE. Fig. 3 shows the distribution of these differences for each country.

Inclusion of indirect losses (Fig. 3, black bars) made SyNE smaller than NUE by a mean of 1% for the EU-27 member states. Although generally a small effect, inclusion of indirect losses is important because it enables small importers such as Eastern European countries (e.g. Slovakia, Latvia, Lithuania, Romania) to be compared to large importers such as Malta, the Netherlands and Belgium.

Inclusion of net flows (Fig. 3, white bars) made SyNE smaller than NUE by a mean of 5%. It decreased the N efficiency of countries that imported feed with the same CP content as that of the crops they produced (e.g. Malta, Belgium, Portugal, Greece). Countries that imported less feed (e.g. Bulgaria, Hungary) were less affected, as were countries that imported feed with a different CP content than that of the crops they produced (e.g. Ireland, Finland).

Change in soil N best explained the difference between SyNE and NUE ($r = -0.77$, $p < 0.001$). Inclusion of changes in soil N made SyNE smaller than NUE by a mean of 7% (Fig. 3, dark gray bars). This factor decreased the N efficiency of countries with more annual crops (e.g. Romania, Hungary, Bulgaria) and increased it for countries with more permanent crops and grasslands (e.g. Ireland, Greece, United Kingdom).

The inclusion of indirect losses, changes in soil N and net flows significantly modifies the interpretation of N efficiency for the EU-27 member states. For instance, the NUE of Ireland is 0.20, while the NUE of Estonia is 0.38, which leads to the conclusion that Estonia is much more efficient than Ireland. Their SyNE values, however, are similar (0.20 for Ireland and 0.19 for Estonia), mostly due to different changes in soil N. Given these improvements, SyNE seems more relevant for comparing the N efficiency of member states that do not have similar input intensities or land uses.

Unlike NUE, SyNE expresses the overall efficiency of agriculture from cradle to the gate of the "territory-farm". These boundaries, inspired by agricultural life cycle analysis, are similar to those used to calculate the nitrogen footprint of agricultural production for a given country (Leach et al., 2012). These boundaries also enable identifying pollution transfers due to the importation of certain inputs such as feed or young animals. It is also a step towards "full-chain NUE" (Sutton et al., 2013), which has similar agricultural boundaries but also includes steps to the final consumer (i.e. food transformation, distribution, consumption, waste management).

3.3. Utility of relative N efficiency at the territory scale

RNE varied from 0.28 to 0.78 among countries (Table 3). SyNE and RNE were correlated ($r(25) = 0.75$; $p < 0.001$) but had notable differences in rank for certain countries (Fig. 4).

RNE expresses the efficiency of a country's agricultural sector according to its potential, which depends on the nature of agricultural production. For instance, Ireland has the same SyNE as the Czech Republic (0.20), but has a better RNE (0.56 versus 0.32) due to its higher percentage of animal production (Fig. 4). In general, countries more specialized in animal production have the greatest relative difference between RNE and SyNE (Fig. 5) due to the inherently low efficiency of animal production. Ireland, Luxembourg, Slovenia and the Netherlands exhibit the greatest increase in efficiency ranking, while Bulgaria and Hungary exhibit the greatest decrease.

One limitation of the SyNE indicator is that it cannot compare countries with different types of production. RNE resolves this issue and is a valuable tool to compare countries and estimate the room for improvement in N efficiency given each country's production mix. Using this indicator, the Czech Republic (RNE = 0.32) has a greater progress margin than Malta (RNE = 0.44) and Ireland

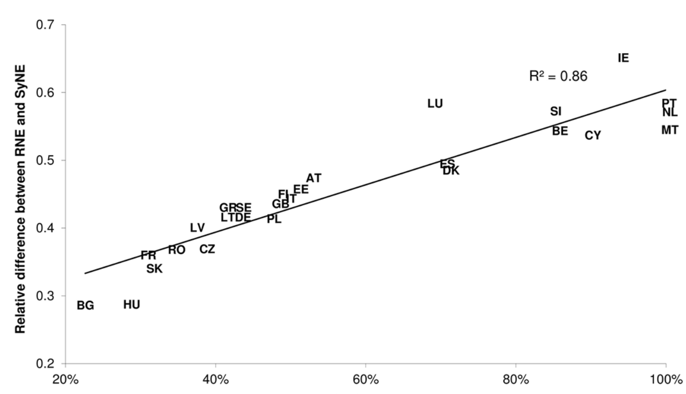

Fig. 5. Relative difference between RNE and SyNE as a function of the percentage of net animal products in national net output for the EU-27 member states for the 2000–2008 period. Relative difference between RNE and SyNE = (RNE–SyNE)/RNE.

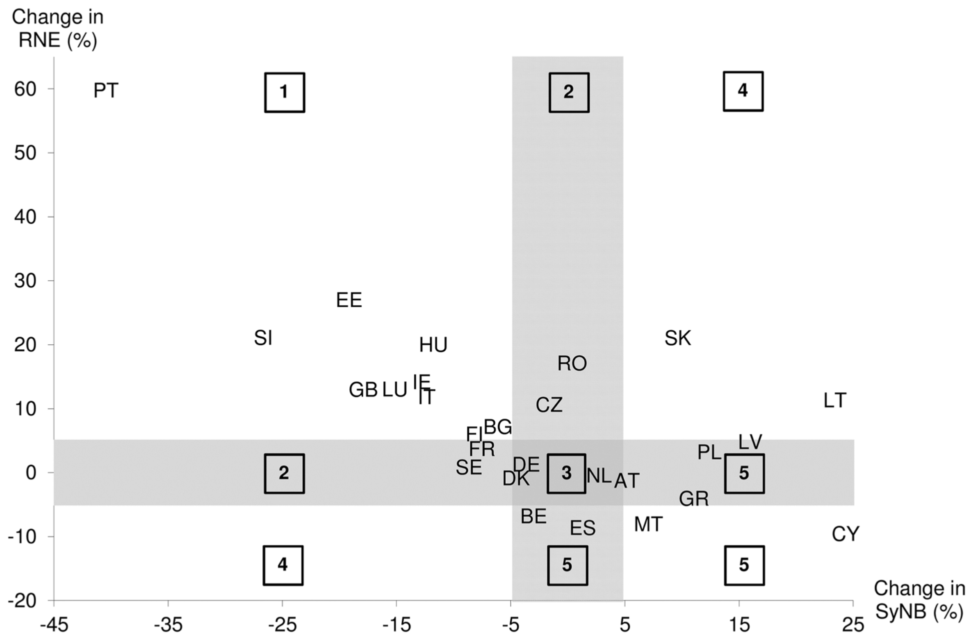

Fig. 6. Change in relative N efficiency (RNE) and system N balance (SyNB) for the EU-27 member states from 2000–2002 to 2006–2008. The gray zones indicate changes of less than ±5% that were not considered significant. Five groups of countries are delimited by these gray zones and identified by numbers in black squares. Group 1: improvement of both indicators; group 2: improvement of one indicator with no change of the other; group 3: no significant change of both indicators; group 4: improvement of one indicator and degradation of the other; group 5: degradation of one indicator with no change of the other or degradation of both indicators.

(RNE = 0.56), although these three countries have a similar SyNE of 0.20.

This indicator provides supplementary information to analyze links between efficiency, N management and production changes. For instance, Poland's SyNE was stable during the 2000–2008 period, but its RNE slightly increased. This indicates an improvement in N management (better RNE) and an increase in the percentage of animal products in total outputs. In Denmark, SyNE decreased and RNE remained stable, indicating an increase in animal products in total output and constant technical efficiency.

3.4. Utility of SyNB and its complementarity with SyNE and RNE

The mean national SyNB is 113 kg N ha^{-1} AA for the 27 member states (Table 3) and ranges from 31 to 432 kg N ha^{-1} AA (Greece and Malta, respectively). SyNB shows a strong correlation with net animal production ($r = 0.96$; $p < 0.001$) and net feed input ($r = 0.94$; $p < 0.001$). FGB was not calculated in this study but we used data from Leip et al. (2011b). Unweighted average FGB was 91 kg N ha^{-1} AA for the 27 member states. The correlation between SyNB and FGB was very clear ($r(25) = 0.94$; $p < 0.001$). Soil N loss and indirect losses explained the 22 kg N ha^{-1} AA of difference between the two indicators.

Ondersteijn et al. (2002) discussed the mathematical link between FGB and NUE. It is negative by construction, meaning that for a given productivity level, the higher the FGB is, the lower the NUE. This relationship also occurs between SyNB and SyNE or RNE but depends on the productivity level of each country. For a RNE of 0.52, SyNB varies from less than 70 kg N ha^{-1} AA (United Kingdom) to over 300 kg N ha^{-1} AA (Netherlands), depending on the productivity level (Table 3). Similarly, for a SyNB close to 50 kg N ha^{-1} AA, RNE varies from 0.28 (Latvia) to 0.78 (Austria).

Efficiency indicators are useful to raise awareness among farmers, agricultural advisors and decision makers (Sutton et al., 2013). These indicators can be used alone but they are complementary to balance indicators (Godinot et al., 2014), and their combined use is particularly relevant in the context of agro-ecology and ecological intensification, which aim to increase global food production while reducing N losses. We therefore recommend using efficiency and balance indicators together whenever possible to get a better understanding of N management at territory scale. These indicators have been developed at farm scale and are adapted to it, but we think that they are also valuable for decision makers at territory scale.

3.5. Change in efficiency indicators and system balance

To study the change in indicator values over time, we calculated a three-year moving average for each country for the 2000–2008 period. This was intended to reduce the influence of variations in climate and stocks on annual indicator results, since these variations are sometimes large between years (Oenema et al., 2003; Westhoek et al., 2014). A linear regression was calculated for each country from the seven three-year averages. These regressions express trends for each of the three indicators.

From 2000–2002 to 2006–2008, SyNE increased more than 5% for 16 countries and decreased more than 5% for 5 countries. It increased more than 20% for Hungary, Slovakia, Estonia and Portugal, in increasing order, but decreased more than 20% for Cyprus.

RNE increased more than 5% in 14 countries and decreased more than 5% in four countries (Fig. 6). On average, this led to an 8% increase during the period. RNE increased more than 20% for five countries: Hungary, Slovakia, Slovenia, Estonia and Portugal, in increasing order.

At the same time, SyNB decreased more than 5% for 12 countries and increased more than 5% for eight countries (Fig. 6). On average, this led to a 3% decrease in SyNB during the period. SyNB decreased more than 20% for Slovenia and Portugal but increased more than 20% for Lithuania and Cyprus.

Due to the high productivity of European agriculture, Buckwell et al. (2014) recommend focusing on ecological intensification to improve environmental performances while keeping the desired output stable. This is the trend observed in EU-27 member states for the 2000–2008 period. Net production remained stable while SyNB slightly decreased due to improved N efficiency (both SyNE and RNE). However, different trends occurred due to different situations and "starting points" (indicator means for 2000–2002) for the 27 member states. Five major trends were identified and countries were grouped accordingly (Fig. 6). Countries in group 1 improved both RNE and SyNB over the period (over 5% increase in RNE and over 5% decrease in SyNB); countries in group 2 improved either RNE or SyNB while keeping the other indicator stable (± 5%); countries in group 3 kept both indicators stable; countries in group 4 improved one of the indicators while degrading the other (over 5% decrease in RNE or over 5% increase in SyNB); finally, countries in group 5 degraded one indicator while keeping the other stable, or degraded both indicators.

All countries in group 1 improved RNE and SyNB. However, some countries also increased their mean net output while some others did not (data not shown). Bulgaria, Estonia, Hungary and Italy improved their productivity while reducing their N balance, thus improving their efficiency. This is mostly explained by low efficiency at the beginning of the period. These countries had a lower RNE than the EU-27 mean (except Italy), giving them an above-average potential for improvement. Other countries in group 1 improved N balance and kept productivity stable (i.e. Finland, Ireland, Luxembourg, Portugal), which corresponds to the ecological intensification described by Buckwell et al. (2014). A third category is observed in group 1: countries with improving SyNB and RNE but decreasing productivity, such as the United Kingdom and Slovenia. Although this does not strictly follow the definition of ecological intensification, this trend shows that moderate extensification can offer an interesting compromise between productivity and environmental impacts.

Improving efficiency while keeping N balance stable (group 2) is another form of ecological intensification. It was particularly relevant for countries with a moderate N balance, such as Romania and the Czech Republic (Fig. 6). SyNB decreased but efficiency remained stable (group 2) for France and Sweden, corresponding to extensification. This is not an issue for France, which has above-average productivity. In contrast, Sweden has lower productivity than the European mean, and further extensification challenges its food production capacity.

Countries in group 3 had no significant pattern of change in their indicators during the 2000–2008 period. This is not a problem for Germany, which had a high relative efficiency and an average N balance. However, this is more problematic for Denmark and the Netherlands, which had a high N balance.

An increase in both system N balance and efficiency (group 4) does not correspond to ecological intensification, but still appears acceptable when system efficiency increases while the N balance remains moderate. This was the case for Latvia, Lithuania and Slovakia, which had balances lower than the EU-27 mean.

Countries in group 5 exhibited trends toward a decrease in efficiency and/or an increase in system N balance. This was especially problematic for countries with a high N balance (Malta, Cyprus) or extensive production (Spain, Greece). The presence of Austria in this group is explained by a decline in its performance due to a highly efficient "starting point"; however, it remained the most efficient and had one of the lowest system N balances in Europe.

Analyzing these trends with combined indicators helps in evaluating public policies, such as the Common Agricultural Policy (CAP). For example, Lassaletta et al. (2014a) have shown that the N efficiency of most European countries has increased thanks to a reduction of N losses during the last 20 years; the main driver of this evolution is thought to be the CAP's environmental regulations.

3.6. Limitations of the study

3.6.1. Considering agro-ecological potential

When calculating RNE, maximum attainable efficiency was identical for all European countries. Calculations ignored climate, terrain and soil characteristics, which is a significant limitation of this indicator. Countries with higher RNEs (>0.45) have temperate and rainy climates (Fig. 7). Conversely, countries with lower RNE have colder climates (e.g. Sweden, Finland, Estonia, Lithuania, Latvia) or hotter and drier climates (e.g. Spain, Portugal, Cyprus, Malta, Greece). Several countries with lower RNE also have lower soil fertility (e.g. Northern and Southern Europe; FAO and IIASA, 2012).

Numerous physical and chemical factors influence N use efficiency. For instance, wind, temperature, pH and soil texture influence N fertilizer volatilization (Bouwman et al., 2002). Precipitation and temperature have a major influence on nitrate leaching (Hyytiäinen et al., 2011; Stark, 1996). Water stress, temperature and phosphorus availability in the soil influence plant N uptake efficiency (Payne et al., 1995; Sheng et al., 2011). A spatially explicit model, called Global Agro Ecological Zones (GAEZ; FAO and IIASA, 2012), details soil, climate, and terrain characteristics as well as soil moisture and photoperiod, among other parameters, for the entire world at a resolution of 1 km^2. This model also provides potential yield indicators for 49 crop types. However, it is not possible to derive potential efficiency from potential yield because of the unclear statistical links between them; van Noordwijk and Brussaard (2014) suggest considering them as independent. It might be possible to use soil and climate data as factors to modulate attainable efficiency according to the context of each territory instead of using a single value for all of them. Given the simplifying assumption used to calculate RNE in this study, when comparing countries, it is important to note that their differences in RNE are not solely due to N management skills.

On the other side, comparing crop production efficiency relatively to the highest existing potential allows identifying the most suited places for crop production given their soil and climate. Producing products where they have the highest potential efficiency might also be an objective.

3.6.2. Limits due to data uncertainty

We could not perform uncertainty analysis due to the lack of information about uncertainty for most variables. Change in soil N is probably one of the most uncertain variables used in calculating these indicators (Wang and Hsieh, 2002). We used a single value for change in soil N for annual crops and another value for change in permanent crops and grasslands. However, the model of Vleeshouwers and Verhagen (2002) has a high standard deviation around the mean (-830 ± 400 kg C ha^{-1} AA $year^{-1}$ for annual crops; $+520 \pm 640$ kg C ha^{-1} AA $year^{-1}$ for permanent crops and grasslands) which expresses both uncertainty and variability in model estimates. The CarboEurope Integrated Project (Ciais et al., 2010a, 2010b) suggested less uncertain estimates for annual crops (130 ± 330 kg C ha^{-1} AA $year^{-1}$) and grasslands ($+740 \pm 100$ kg C ha^{-1} AA $year^{-1}$). We explored the use of these estimates, but they resulted in storage of organic carbon in the soil for 24 of the 27 member states, which contradicts most recent studies (Arrouays et al., 2002; Bellamy et al., 2005; Sleutel et al., 2003; Smith et al., 2005). Thus, we chose the more uncertain estimates from Vleeshouwers and Verhagen (2002). Given the high uncertainty in this variable, estimates for France (-27 kg N ha^{-1} AA $year^{-1}$) lay in the same order of magnitude as those of Arrouays et al. (2002) of -13.3 kg N ha^{-1} AA $year^{-1}$. For the United Kingdom, Bellamy et al. (2005) estimated a net loss of organic carbon (and thus nitrogen) of 0.6% $year^{-1}$ from 1973 to 2003, while our estimate was a small net storage of organic N (5 kg N ha^{-1} AA $year^{-1}$). Our

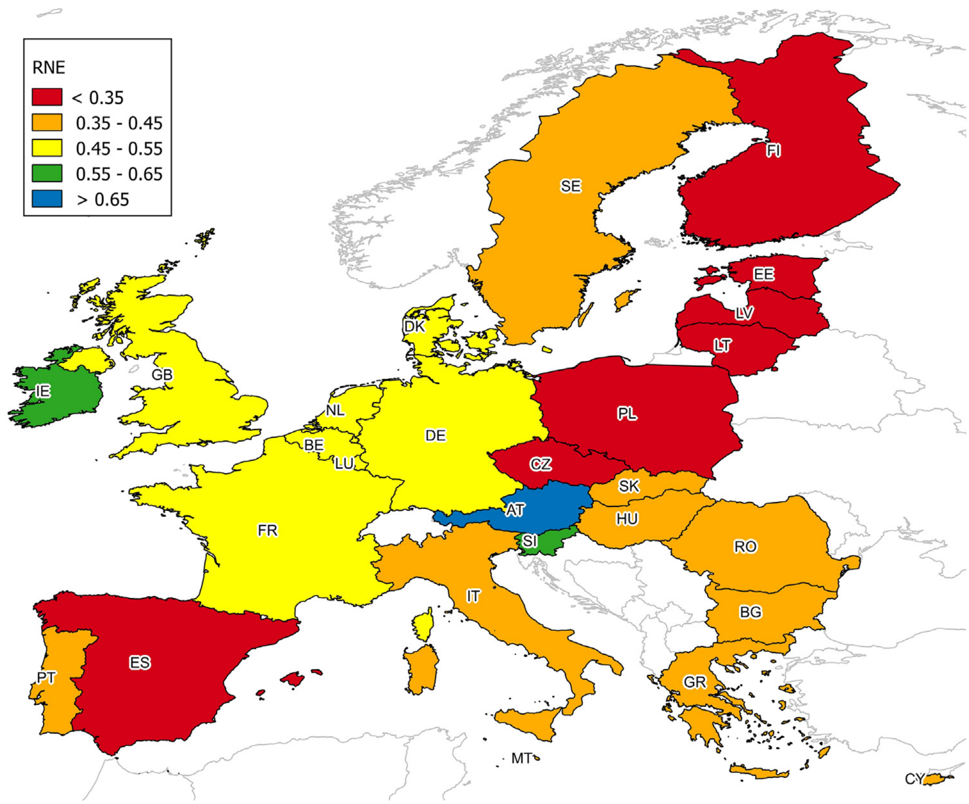

Fig. 7. Map of relative N efficiency (RNE) of the EU-27 member states during the 2000–2008 period.

method, although less favorable for N storage than CarboEurope IP, still seemed to overestimate it for the United Kingdom.

The estimated biological N fixation (1498 Gg N year^{-1} for the EU-27 from 2000 to 2008; EUROSTAT, 2014) is higher than that from other sources, such as the EU FP7 project Legume Futures (810 Gg N in 2009; Baddeley et al., 2014), the results of various models (800–1400 Gg N; de Vries et al., 2011), and the European Nitrogen Assessment (1000 Gg N in 2000; Leip et al., 2011a). This discrepancy can be explained by the EUROSTAT data including non-symbiotic BNF by free-living organisms (4 kg N ha^{-1} for annual crops; OECD and EUROSTAT, 2007). Without it, symbiotic fixation from legumes is 1055 Gg N for the EU-27. Although uncertain, this value is similar to that of other studies. Non-symbiotic fixation, despite its high uncertainty (EUROSTAT, 2013; Herridge et al., 2008), was also included in the calculation of indicators to respect the mass-balance principle. We considered that including all N inputs improved the quality of our indicators despite increasing their uncertainty.

Life cycle inventory data were used to estimate indirect losses. However, most of these data are characteristic of French production standards and use typical distances from French import harbors (Godinot et al., 2014) because detailed data were not available for each member state. This assumption seems acceptable for soybean, the main feed input, although transport is potentially greater for Eastern European countries with no access to the sea. This assumption is more uncertain for feed crops produced in European countries that have agricultural practices that differ from the French average. Indirect losses must be considered an uncertain estimate of the true losses due to input production and transport.

3.6.3. Limits due to the scale of approach

The main limit of the national scale is its low level of detail. National averages hide important differences between regions. For instance, it is possible to have an acceptable system N balance at the national scale but severe N losses in an intensive livestock region. Several spatially explicit models can disaggregate national data at the regional scale (Leip et al., 2008) or at the local scale (Velthof et al., 2014). Our methods and models could calculate N efficiency (SyNE, RNE) and balance (SyNB) at smaller scales.

Increasing the scale of approach based on national data is also difficult. For instance, the average of EU-27 member states used to compare countries in our study does not represent Europe. This is because we used unweighted means in order to compare countries with major discrepancies in agricultural area, amount of production, etc. Area-weighted or production-weighted means cannot represent the EU either, because the system boundaries are modified when the scale changes. For instance, crop production from a member state used as animal feed in another are respectively considered an output and an input at national scale, but would be considered as an internal flow at the European scale. Estimating the N efficiency and balance of the EU would require knowing which inputs come from member states and which come from countries outside the EU, and the share of outputs used in the agricultural sector.

4. Conclusion

This study demonstrates the feasibility and utility of calculating N efficiency and balance indicators at the national scale. The three indicators developed (SyNE, SyNB and RNE) are not directly comparable to existing references due to methodological differences but are consistent with them. The indicators are calculated according to a systems approach that includes activities upstream of agricultural production (from cradle to farm gate). This integrative approach enables relevant comparisons between countries with different production methods and intensities. Our method considers change in soil N, an influential variable that is rarely considered. Although estimates of change in soil N are uncertain, its inclusion renders comparisons of countries more valid. Future research to estimate changes in soil N is necessary to reduce uncertainty in these indicators.

Combined use of the three indicators provides new insights into N management. System efficiency and balance are complementary concepts for evaluating the use of N resources in agriculture and the resulting environmental pressure. Relative efficiency enables assessing the progress margin of each country given its production, and enriches the efficiency analysis by considering the nature of agricultural products. Studying these indicators over time helps to understand and assess the evolution of a country's agricultural sector and helps evaluate effects of public policies. These indicators are promising tools to study, compare and improve the N efficiency of territories or countries.

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