Agricultural Systems 162 (2018) 28–33

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Short Communication

A free online tool to calculate three nitrogen-related indicators for farming systems

Matthieu Carof*, Olivier Godinot

SAS, AGROCAMPUS OUEST, INRA, 35042 Rennes, France

ARTICLE INFO

Keywords:
Farming system
Indicator
Nitrogen efficiency
Nitrogen balance
Online calculator

ABSTRACT

Reactive nitrogen (N) is a key agricultural input, essential for crop growth and production, but excess N in the environment causes problems for human and ecological health. One of the most promising solutions for reducing environmental impacts of excess N levels and feeding a growing population is to improve N efficiency of farming systems i.e., increase the ratio of their N output to N input. Assessing promising solutions involves calculating N efficiency, which is not trivial. For this reason, a free online tool was developed – the SyNE calculator, https://www.nefficiencycalculator.fr/en/ – to allow farmers, farm advisors, researchers, and policy makers to calculate three N-related indicators of farming systems: SyNE, an N efficiency indicator; SyNB, an N balance indicator; and RNE, a relative N efficiency indicator. After entering information about a farming system, the SyNE calculator produces two main outputs: first, values of the three indicators (SyNE, SyNB, and RNE) and those of related variables (N inputs, N losses during production and transport of inputs, N outputs, and change in soil N); second, a downloadable diagram showing these values. The main advantages of this tool are that it (i) simplifies N indicator calculation, using the same scientific framework for all farming systems, and (ii) includes many reference values that are difficult to obtain (e.g., N losses during production and transport of inputs). Furthermore, this tool allows advanced users to modify the values and equations used to calculate the three N-related indicators. The SyNE calculator is currently available for farms producing dairy cattle, beef cattle, and field crops; in the near future, it will be available for farms producing pigs and broilers. If used, this online tool will contribute to the development of N efficiency evaluation by farmers, farm advisors, and researchers, which may result in improved agricultural N management practices.

1. Introduction

Anthropogenic disruption of the biogeochemical nitrogen (N) cycle is one of the most pressing threats to the environment: the current level of reactive N use is estimated at 240% of the planetary boundary (Steffen et al., 2015). Agriculture is by far the main user of N, in the forms of synthetic fertilizers and biological N fixation for food production (de Vries et al., 2013). At the global scale, N efficiency (defined as N output/N input) is 38% for crop production and approximately 10% for animal production (de Vries et al., 2013; Gerber et al., 2014). To feed a growing population while reducing N burden on the environment, one of the most promising solutions is to improve N efficiency in agriculture (Bodirsky et al., 2014; Sutton et al., 2013, 2011), although this will not be sufficient alone to counteract the increase in N losses due to increased food production (Bouwman et al., 2013; Regan et al., 2016).

Decision aid tools are quite common in agriculture (see for example, Rose et al., 2016): they help end users manage, understand, and share knowledge about complex agricultural systems (Yost et al., 2011). For farmers and farm advisors, decision aid tools facilitate farm management by analyzing on-farm data and generating evidence-based recommendations (Rose et al., 2016). For researchers, decision aid tools allow them to evaluate agronomic and environmental efficiency of agricultural systems in order to build more sustainable ones (Bockstaller et al., 1997). For policy makers, decision aid tools are of particular interest to understand consequences of their decisions, which are often long term and irreversible, and to present them in a transparent way (Serrat-Capdevila et al., 2011). Decision aid tools may be based on indicators which, by condensing scientific information, help to simplify reality and make it accessible to decision makers (Girardin et al., 1999).

N Balance and N Use Efficiency (NUE) are the two N indicators most used at the farm scale (Langeveld et al., 2007; Rasmussen et al., 2017). They have some significant limitations, however: farm gate system boundaries are not large enough to assess farms with substantial N inputs (Einarsson et al., 2018); change in soil N is usually not

* Corresponding author: AGROCAMPUS OUEST, 65 rue de Saint-Brieuc, CS 84215, F-35042 Rennes cedex, France.
E-mail address: matthieu.carof@agrocampus-ouest.fr (M. Carof).

https://doi.org/10.1016/j.agsy.2018.01.015
Received 18 July 2017; Received in revised form 17 January 2018; Accepted 17 January 2018
0308-521X/ © 2018 Elsevier Ltd. All rights reserved.

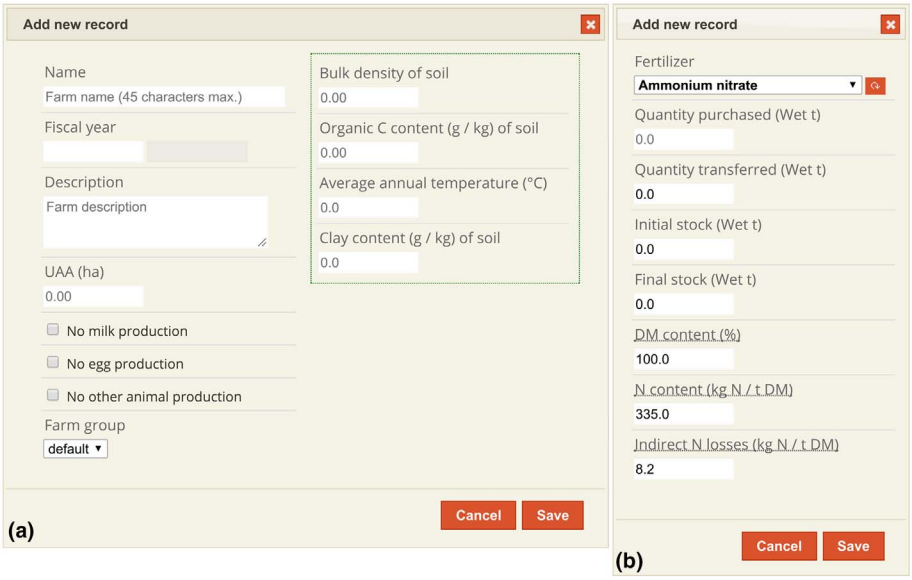


Fig. 1. Examples of two user-accessible forms for entering data in the SyNE calculator. Form (a) allows end users to enter data for a new farming system (e.g., arable land area (UAA), types of production, main soil characteristics). Form (b) allows end users to enter data for purchased nitrogen (N) fertilizers. In this example, purchased N fertilizer is ammonium nitrate: default values are set for three fields – dry matter (DM) content, N content, and indirect N losses (i.e., those during production and transport of inputs) – but end users can change them.

considered (Watson and Atkinson, 1999); manure N can be considered a product or not, which is inconsistent (Godinot et al., 2014); and finally, there is an arithmetic bias in the NUE indicator (Schröder et al., 2003; see the "purchase-resale" bias of NUE, described below).

Three new indicators were developed to address these limitations (Godinot et al., 2015, 2014). In brief, SyNE (System N Efficiency) estimates N efficiency of a farming system i.e., the extent to which N inputs of a farming system are converted into N outputs. SyNE improves NUE (Aarts et al., 1992) in several ways:

- It corrects the "purchase-resale" bias of NUE (i.e., the fact that mathematically, a farming system relying on external inputs has a higher NUE than a self-sufficient one (all else being equal)).
- It considers N losses during production and transport of inputs (based on principles of life-cycle assessment (LCA)).
- It considers changes in soil N, unlike NUE, which assumes that soil N content does not vary.

Since performances of a farming system rely not only on N efficiency but also on N losses it generates, SyNE must be used along with SyNB (System N Balance), which estimates potential N losses in a farming system (i.e., the sum of N inputs, N losses during production and transport of inputs, and change in soil N, minus N outputs). Finally, since animals have lower N efficiency than crops, current N efficiency indicators cannot compare farming systems with different types of production. To address this issue, RNE (Relative N Efficiency) expresses N efficiency relative to that attainable by crop and animal products.

These three new indicators were subjected to a validation phase, as recommended by Girardin et al. (1999). According to Bockstaller and Girardin (2003), an indicator can be validated in three ways:

- "Design validation" evaluates whether the indicator is built on rigorous science. We posit that publication of the development and application of indicators in international peer-reviewed journals is a good guarantee of their scientific quality. Godinot et al. (2015, 2014) have done so, discussing their added value. Moreover, several recent publications have highlighted advantages of using comprehensive N efficiency indicators that include N losses occurring outside farm boundaries (Bodirsky et al., 2014; Mu et al., 2016; Sutton et al., 2013; Uwizeye et al., 2016).
- "Output validation" evaluates the soundness of outputs by comparing them to measures or outputs of other indicators; comparison of these three indicators and other existing indicators for 27 European Union (EU) Member States showed that estimates of the former were consistent with existing knowledge about agriculture of the Member States (Godinot et al., 2016).
- "End-use validation" addresses implementation of the indicator as a decision aid tool, whether it is used, and how. N Balance and similar variants have been used by farmers, farm advisors, researchers, and decision makers for several decades to assess N pressure on the environment (Oenema et al., 2003). In contrast, NUE, although available for at least 25 years (e.g., Aarts et al., 1992), is still almost only used by researchers, although some decision makers are willing to use it (Eurostat, 2017).

If we want end users to use these new indicators, we need to show their utility as decision aid tools, and facilitate their implementation. To this end, we developed the online calculator described here.

2. Overall description of the SyNE calculator

The source code of the SyNE calculator was written using HyperText Markup Language (HTML), Cascading Style Sheets (CSS), JavaScript, PHP, and Structured Query Language (SQL). The first three languages are used to create multimedia and interactive web pages, while PHP and SQL are used to manage data stored in a MySQL database and to run calculations with these data. Input data and calculated results are stored in the MySQL database.

The SyNE calculator is available online, free of charge, at https://www.nefficiencycalculator.fr/en/. End users need to create an account (using name, e-mail address, and password) to store their data securely on our institution's servers. By default, the ability for end users to modify parameters is limited but can be extended on request; since each account has a copy of the default parameter set, validated by the designers of the SyNE calculator, parameter changes by an end user affect only that user's data and calculations.

The SyNE calculator computes the three N-related indicators (SyNE, SyNB, RNE) for a farming system (i.e., the combination of productive activities at the farm level (Le Gal et al., 2010)). To calculate the three indicators, end users enter data describing (i) main characteristics of a farming system (e.g., arable land area, types of production, main soil characteristics), (ii) crop production (e.g., crop areas, yields, seeding rates, crop residue management), (iii) animal production (e.g., numbers of animals, types of animal housing, lengths of grazing periods), (iv) purchases of animal feed, inorganic fertilizer, and manure, and (v) sales of animal and crop products (Fig. 1). About 15 min are required to enter

values for one farming system. End users can duplicate input data of each farming system, which allows them to store (and then use) input data corresponding to many individual years. Also it allows them to test virtually changes to a particular farming system without losing the original data.

N inputs, N losses during production and transport of inputs, and N outputs are then calculated, using the data previously entered and reference values for N contents, N fixation rates, etc. (end users can easily change these values). Reference values are those described in Godinot et al. (2015, 2014). Change in soil N is calculated using equations from AMG, a model that simulates soil carbon (C) dynamics (Andriulo et al., 1999). C:N ratios for crops, animal manure, and soil organic matter are used to convert amounts of C into amounts of N.

For each farming system, the SyNE calculator produces two main outputs that can be downloaded: (i) a comma-delimited file containing farm input data and calculator results (i.e., net N inputs, net N losses during production and transport of inputs, net N outputs, change in soil N, SyNE, SyNB, and RNE) and (ii) a diagram with these values. Net inputs, net losses during production and transport of inputs, and net outputs correct the "purchase-resale" bias of NUE and are explained in Godinot et al. (2014).

The SyNE calculator was tested using farm data described by Godinot et al. (2014): 38 mixed dairy-crop farming systems in south-eastern Brittany, France, surveyed in spring 2012. The information collected included 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. The data are available in Carof and Godinot (submitted). The test involved a simple comparison of the values obtained by the SyNE calculator vs. those obtained by the original Excel® spreadsheet used by Godinot et al. (2014).

3. Examples of results

Values of N inputs, indirect N losses, N outputs, change in soil N, SyNE, SyNB, and RNE for the 38 farming systems were calculated using the SyNE calculator. Since results produced by the SyNE calculator were identical to those produced by the original Excel® spreadsheet, we considered the calculations, and therefore the source code, of the SyNE calculator to be valid.

Graphing RNE vs. SyNE (Fig. 2) highlights the utility of using them together. Crop-oriented farming systems tend to have higher SyNE than animal-oriented farming systems, but within each category, some farming systems are closer to their potential efficiency given their specific product mix. It is thus a useful tool to assess the leeway for increasing N efficiency of farming systems. It also allows for more relevant comparisons of mixed farming systems that produce different proportions of crops and livestock.

We illustrate application of the calculator using one of the 38 farming systems as an example: a system with 57.55 ha on silt loam soil that produced 413 359 L of fat-and-protein-corrected milk from 55 Holstein Friesian dairy cows. Its cattle feeding system was based on forages produced on-farm (temporary grasslands for grazing and harvesting, stored as hay and silage; alfalfa and maize for harvesting, stored as silage) and purchased feed (grass hay, N-rich pelleted feed, wheat straw). Dairy cows were housed on a fully-slatted concrete floor, while other cattle classes (dairy heifers, calves) were housed on straw bedding. Cropping systems included temporary grassland (grass only, grass and legumes), maize, winter wheat, and alfalfa; winter wheat was the only crop grown as a cash crop. Purchased inorganic fertilizers were ammonium nitrate, 14-10-20 fertilizer, 13-30-0 fertilizer, and 20-20-0 fertilizer. Some of the manure produced by dairy cows was transferred to another farming system, while some chicken manure was purchased. The diagram of the farming system's N flows generated by the calculator (Fig. 3) helps end users understand the importance of N flows that are usually ignored by other indicators, such as indirect N losses caused by input production and transport, and changes in soil N content. On this farming system, for instance, indirect N losses, which are usually not estimated by farmers, exceeded the N content of the animal (i.e., meat) output.

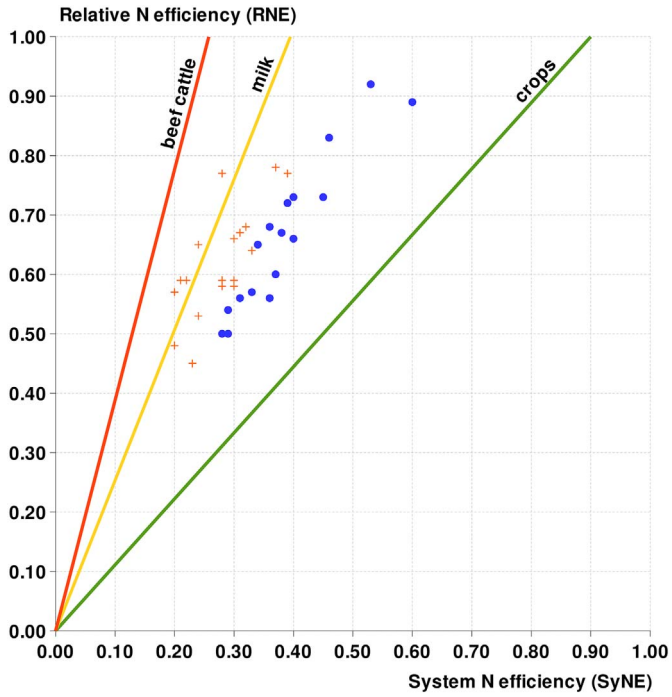


Fig. 2. Comparison between Relative Nitrogen Efficiency (RNE) (unitless) and System Nitrogen Efficiency (SyNE) (unitless) for 38 mixed crop and dairy farms in Brittany. Farm data come from Godinot et al. (2014) and are available in Carof and Godinot (submitted). Diagonal lines represent relationships between RNE and SyNE for specialized farming systems with 100% RNE, equal to potential efficiency for a given product (Godinot et al., 2015). Orange crosses represent farming systems producing > 50% of their nitrogen (N) outputs as animal products, while blue circles represent those producing > 50% of their N outputs as crops. Three outliers with RNE > 1 are not shown.

4. Discussion

4.1. Novelty of the SyNE calculator

Some user-friendly tools already exist to calculate the usual indicators NUE and N Balance (see for example, Evans et al., 2016; Wheeler et al., 2006). To our knowledge, the SyNE calculator is the first one that computes SyNE, SyNB, and RNE, three new N-related indicators that provide higher quality information about N efficiency and N losses than NUE and N Balance (Godinot et al., 2015, 2014).

Furthermore, the SyNE calculator helps resolve the lack of decision aid tools for environmental management of N at the farm scale, as identified by Meynard et al. (2002). For this purpose, it would be of particular interest to use it with a decision aid tool for single-field N management; this approach would improve N management of farming systems both in the field and on the farm, avoiding contrary scale-dependent effects of N management.

4.2. Design method for the SyNE calculator

Bockstaller et al. (2009) and Rose et al. (2016) developed lists of criteria to consider when designing indicator-based tools. The SyNE calculator meets some of them, as described below.

It addresses only one environmental issue (i.e., in-depth analysis of N use in agriculture) but does so for a variety of farming systems (dairy cattle, beef cattle, field crops). One current limitation is that it does not address other major farming systems, such as those producing pigs or

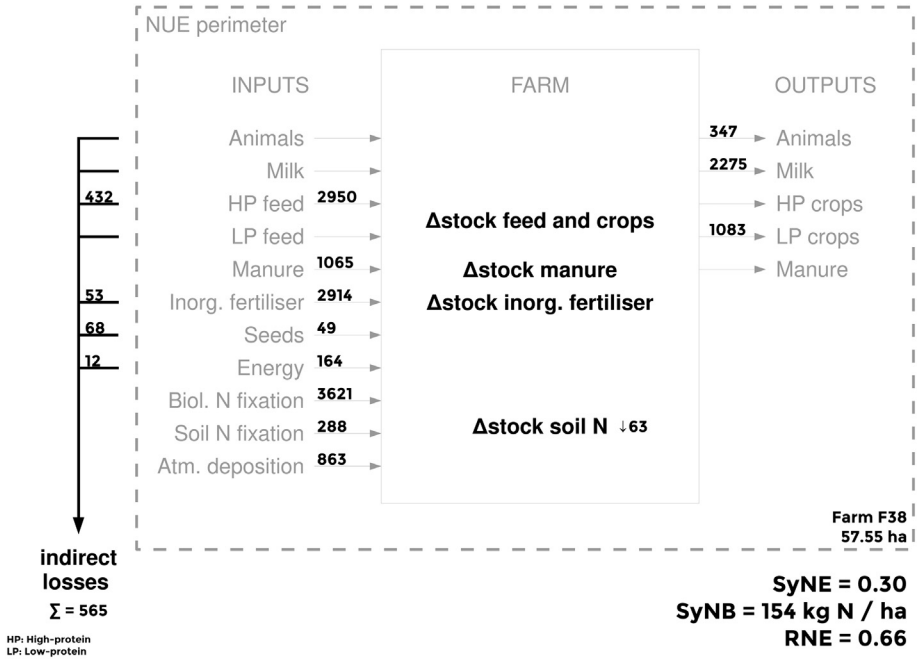


Fig. 3. Example of a diagram produced by the SyNE calculator, showing net nitrogen (N) inputs, net indirect N losses, net N outputs, change in soil N, and the three N-related indicators (System N Efficiency, SyNE; System N Balance, SyNB; Relative N Efficiency, RNE) computed by the calculator. All values are expressed in kg N, except for SyNE and RNE, which are unitless, and for SyNB, which is expressed in kg N ha^{-1}. Net inputs, net indirect losses, and net outputs are explained in Godinot et al. (2014).

broilers.

The SyNE calculator is freely available for use after online registration and, in the interest of transparency, all data used to calculate the three indicators are available in the tool (e.g., Table 1). Only advanced end users, however, can access the entire dataset, so as not to discourage novice end users by providing them with more information than they need.

One of the main weaknesses of the SyNE calculator is that it was not designed according to a participatory approach, because it was developed outside of a research project, during individual work time of the authors. A participatory approach to the design of a decision aid tool allows designers to consider expectations of end users more precisely and to identify situations in which the tool will be used (Cerf et al., 2012; Prost et al., 2012). This lack of considering end users during the design process complicates assessment of the SyNE calculator according to user-dependent criteria such as user qualifications, the need for external support, user-friendliness, time requirements, and the quality of the results provided (currently, a downloadable data table and diagram). We plan to survey end users of the calculator to expand its limits and understand how they use it. Interested end users will be involved in the improvement phase.

Table 1
List of default dry matter (DM) and nitrogen (N) contents of animal feeds in the SyNE calculator, including indirect N losses from production and transport of purchased feeds. End users can edit these values and add new feeds for their farming systems.

Feed	DM content (%)	N content (kg N Mg DM^{-1})	Indirect N losses (kg N Mg DM^{-1})
Oat grain	88.0	17.6	11.4
Wheat grain	87.0	20.2	10.1
Barley grain	87.0	18.9	10.3
Triticale grain	87.0	18.7	9.7
Oilseed rape grain	92.0	33.4	29.5
Pea grain	87.0	38.2	21.2
Maize grain	86.0	15.0	11.4
Maize silage	33.0	11.2	4.3
Maize gluten feed	88.0	34.7	11.5
Grass hay	85.0	15.0	6.1
Wheat straw	91.0	6.7	2.0
Rapeseed meal	89.0	61.3	8.0
Linseed meal	91.0	55.0	30.9
Soybean meal	88.0	82.9	9.0
Soybean meal, formaldehyde treated	88.0	74.5	10.9
Concentrate compound (41% protein)	88.0	74.5	21.1
Concentrate compound (18% protein)	87.0	33.1	46.3
Dried alfalfa	91.0	29.3	2.1
Urea	99.0	460.0	2.4
Milk powder	100.0	36.0	1.0

4.3. Intended use of the SyNE calculator

Although the SyNE calculator was not designed according to a participatory approach, we did consider its intended use. It is intended to be used by various target audiences: farmers, farm advisors, researchers, and policy makers.

4.3.1. The SyNE calculator for farmers and farm advisors

One advantage of this tool for farmers and farm advisors is that it includes many reference values that are difficult to obtain, in particular those for indirect N losses (obtained from life cycle inventory data) (Table 1).

Farmers using the SyNE calculator may pay particular attention to RNE, since it compares their farming systems' SyNE to maximum values of SyNE that can be attained by farming systems producing a similar combination of products (Godinot et al., 2015).

In farm support groups, farm advisors and farmers can also compare the RNE of members' farming systems, but they may pay particular attention to SyNE and SyNB, which compare the farming systems' N efficiency (SyNE) and potential for N pollution (SyNB). Using SyNE and SyNB values, group members may identify farming systems' strengths and weaknesses and think about management strategies that could modify N fluxes to increase SyNE and decrease SyNB (Fig. 4). These strategies could be tested virtually using the SyNE calculator.

4.3.2. The SyNE calculator for researchers and policy makers

Like farmers and farm advisors, researchers may be interested in a tool that simplifies calculation of N indicators. This is especially true for multicriteria assessment of farming systems, in which calculation of multiple indicators can be a long and complex task requiring a wide

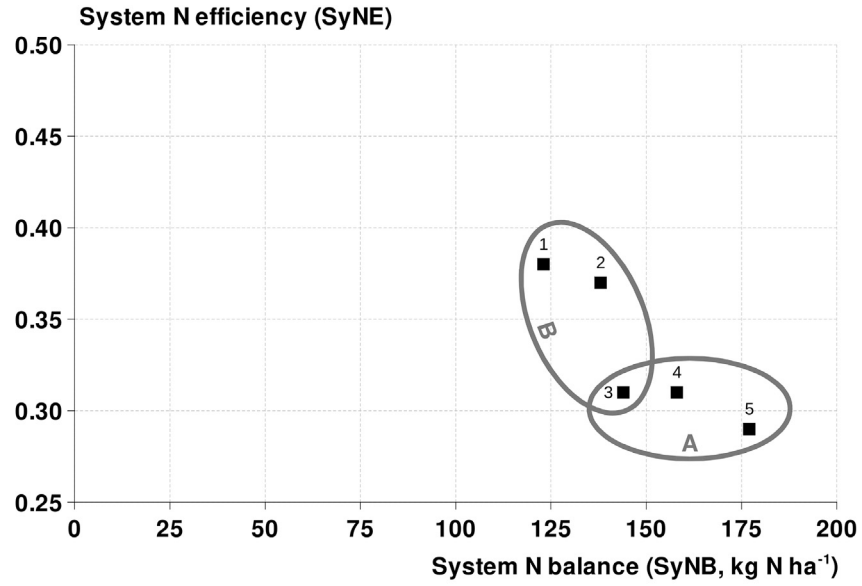


Fig. 4. Relationship between System Nitrogen Efficiency (SyNE) (unitless) and System Nitrogen Balance (SyNB) (kg nitrogen (N) ha^{-1}) for 5 mixed dairy-crop farms in a fictive farm support group. A farm advisor could identify sub-group A, whose strategy is to decrease SyNB without decreasing SyNE. For instance, farms 4 and 5 could adopt some management practices of farm 3 (e.g., decrease fertilizer use, decrease change in soil N). Another sub-group (B) could be identified whose strategy is to increase SyNE without decreasing SyNB. For instance, farm 3 could adopt some management practices of farms 1 and 2 (e.g., increase crop production while using fewer fertilizers and more legumes to fix N). Net N inputs, net indirect N losses, net N outputs, change in soil N, SyNE, and SyNB are computed by the calculator using data described by Godinot et al. (2014) and available in Carof and Godinot (submitted). Net inputs, net indirect losses, and net outputs are explained in Godinot et al. (2014).

	Net output (kg N ha^{-1})		Net input + indirect losses (kg N ha^{-1})				Stock variation
Farm	Animal and Milk	Crops	Fertilizers	Seeds	Feed	Fixation	(kg N ha^{-1})
1	28	46	117	2	18	44	3
2	27	54	89	2	36	61	-13
3	27	39	123	2	28	33	-4
4	29	44	144	3	31	27	-7
5	28	44	150	2	32	31	-16

variety of expert knowledge. For instance, the tool can easily calculate indirect N losses, which would otherwise require LCA methods. The tool can also calculate change in soil N easily, and while the method chosen for doing so has some limitations (Godinot et al., 2014), we argue that considering change in soil N improves the accuracy of results.

The RNE indicator also allows farming systems with different types of production to be compared. It is particularly useful for comparing integrated crop-livestock farming systems. The SyNE of farming systems producing different proportions of animal and crop products is not sufficient to identify those with the best N management practices (Fig. 2), since farming systems producing more crops tend to be more efficient than farming systems producing more milk and meat. Combined use of SyNE and RNE allows farming systems' efficiency to be assessed as a function of their specific product mix. Finally, the tool follows a single assessment method, which allows research results to be compared.

The tool is freely available for use after registration, which will help develop a community of users who can improve default data and provide the tool with new references. A future database of farming systems could also lead to collective work identifying the most efficient farming systems or practices, and could thus be a trigger to develop new research projects on the topic.

Agricultural policy makers could also benefit from these system indicators: the system boundaries chosen, from production of inputs to the farm gate, avoid possible pollution swapping between system components (e.g., related to imported feedstuffs replacing local production), which is not visible with farm-scale indicators. These boundaries are well suited for defining policies that encourage more sustainable use of N in farming systems.

The utility of these indicators at the national scale was shown for 27 EU Member States (Godinot et al., 2016); thus, the tool could also be used to assess N efficiency at regional or national scales. However, when estimating change in soil N, the tool considers only one type of soil. At larger scales, another calculation method for change in soil N would be necessary for better results.

Our tool is complementary with N footprint tool (Leach et al., 2012; www.n-print.org), which aims to sensitize consumers and institutions about the N losses related to their actions. It thus focuses on food and energy from their production to their consumption by end users. In contrast, our N efficiency tool is designed for farmers, farm advisors and agricultural policy makers. Its perimeter is thus more focused on farm activities. We defined our system boundaries in the same manner as those of most agricultural life cycle analyses: “from cradle to farm gate” (i.e., from the production of inputs entering the farm to the products leaving the farm (Clark and Tilman, 2017)). Despite these differences in target audience and study perimeter, both tools have strong similarities. They consider all N flows from the cradle to a targeted user, and they aggregate all N flows in a single indicator rather than expressing impacts of various N compounds on water, air and soil compartments. Both tools also share weaknesses due to using average and estimated input data, and having uncertainty in results. These are, of course, important limitations of both N footprint and N efficiency calculators. It is important to remember, however, that their main objective is not to predict N losses or N efficiency with great accuracy, but to raise awareness about N management and help the targeted audience adopt more sustainable consumption practices (for consumers using the N footprint) or production practices (for farmers using N efficiency).

5. Conclusion

The SyNE calculator presented here is currently available for farming systems producing dairy cattle, beef cattle, and field crops. In the near future, it will also be available for farming systems producing pigs and broilers. In collaboration with future users, we want to increase the amount of data available (e.g., more crops, more livestock feeds) and increase accuracy of the data already available. This tool is of interest because it can (i) be used by farmers and farm advisors to assess and improve N management practices, (ii) support the scientific community in developing more sustainable farming systems, and (iii) help make N efficiency indicators a common assessment tool for

agricultural policy makers. By sensitizing the agricultural sector to the challenge of N efficiency, it complements other indicators such as the N footprint. Like the N footprint calculator, it is also possible to enlarge the study perimeter and use the SyNE calculator at regional or national scales, which could be a more appropriate scale for policy makers.

Acknowledgments

We thank François Tessier, who helped develop the SyNE calculator, and colleagues from the IT Department of AGROCAMPUS OUEST (in particular, Olivier Chénedé) for their technical support for data storage and web services. We also thank Michelle L. Corson and Michael S. Corson for proofreading the English. We are grateful to an anonymous reviewer for constructive remarks and suggestions.

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.

Andriulo, A., Mary, B., Guérif, J., 1999. Modelling soil carbon dynamics with various cropping sequences on the rolling pampas. Agronomie 19, 365–377. http://dx.doi.org/10.1051/agro:19990504.

Bockstaller, C., Girardin, P., 2003. How to validate environmental indicators. Agric. Syst. 76, 639–653. http://dx.doi.org/10.1016/S0308-521X(02)00053-7.

Bockstaller, C., Girardin, P., van der Werf, H.M.G., 1997. Use of agro-ecological indicators for the evaluation of farming systems. Eur. J. Agron. 7, 261–270. http://dx.doi.org/10.1016/S1161-0301(97)00041-5.

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M.-B., Gaillard, G., 2009. Comparison of methods to assess the sustainability of agricultural systems: a review. Agron. Sustain. Dev. 29, 223–235. http://dx.doi.org/10.1051/agro:2008058.

Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A., Stevanovic, M., 2014. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. Nat. Commun. 5 (3858). http://dx.doi.org/10.1038/ncomms4858.

Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proc. Natl. Acad. Sci. U. S. A. 110, 20882–20887. http://dx.doi.org/10.1073/pnas.1012878108.

Carof, M., Godinot, O., 2018. Survey Data From 38 Integrated Crop-livestock Farming Systems in Western France. submitted. (Data in Brief).

Cerf, M., Jeuffroy, M.-H., Prost, L., Meynard, J.-M., 2012. Participatory design of agricultural decision support tools: taking account of the use situations. Agron. Sustain. Dev. 32, 899–910. http://dx.doi.org/10.1007/s13593-012-0091-z.

Clark, M., Tilman, D., 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ. Res. Lett. 12, 064016. http://dx.doi.org/10.1088/1748-9326/aa6cd5.

de Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Curr. Opin. Environ. Sustain. 5, 392–402. http://dx.doi.org/10.1016/j.cosust.2013.07.004.

Einarsson, R., Cederberg, C., Kallus, J., 2018. Nitrogen flows on organic and conventional dairy farms: a comparison of three indicators. Nutr. Cycl. Agroecosyst. 110, 25–30. http://dx.doi.org/10.1007/s10705-017-9861-y.

Eurostat, 2017. Agri-environmental Indicators - Gross Nitrogen Balance. http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_gross_nitrogen_balance, Accessed date: 11 July 2017.

Evans, A., Lucas, D., Blaesing, D., 2016. Nitrogen use efficiency (NUE) and tools for farmer engagement: a good reason for being imprecise. In: Solutions to Improve Nitrogen Use Efficiency for the World. Presented at the 2016 International Nitrogen Initiative Conference, Melbourne, Australia, (p. 4 p).

Gerber, P., Uwizeye, A., Schulte, R., Opio, C., de Boer, I., 2014. Nutrient use efficiency: a valuable approach to benchmark the sustainability of nutrient use in global livestock production? Curr. Opin. Environ. Sustain. 9, 122–130. http://dx.doi.org/10.1016/j.cosust.2014.09.007.

Girardin, P., Bockstaller, C., van der Werf, H., 1999. Indicators: tools to evaluate the environmental impacts of farming systems. J. Sustain. Agric. 13, 5–21. http://dx.doi.org/10.1300/J064v13n04_03.

Godinot, O., Carof, M., Vertès, F., Leterme, P., 2014. SyNE: an improved indicator to assess nitrogen efficiency of farming systems. Agric. Syst. 127, 41–52. http://dx.doi.org/10.1016/j.agsy.2014.01.003.

Godinot, O., Leterme, P., Vertès, F., Faverdin, P., Carof, M., 2015. Relative nitrogen efficiency, a new indicator to assess crop livestock farming systems. Agron. Sustain. Dev. 35, 857–868. http://dx.doi.org/10.1007/s13593-015-0281-6.

Godinot, O., Leterme, P., Vertès, F., Carof, M., 2016. Indicators to evaluate agricultural nitrogen efficiency of the 27 member states of the European Union. Ecol. Indic. 66, 612–622. http://dx.doi.org/10.1016/j.ecolind.2016.02.007.

Langeveld, J.W.A., Verhagen, A., Neeteson, J.J., van Keulen, H., Conijn, J.G., Schils, R.L.M., Oenema, J., 2007. Evaluating farm performance using agri-environmental indicators: recent experiences for nitrogen management in The Netherlands. J. Environ. Manag. 82, 363–376. http://dx.doi.org/10.1016/j.jenvman.2005.11.021.

Le Gal, P.-Y., Merot, A., Moulin, C.-H., Navarrete, M., Wery, J., 2010. A modelling framework to support farmers in designing agricultural production systems. Environ. Model. Softw. 25, 258–268. http://dx.doi.org/10.1016/j.envsoft.2008.12.013.

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. http://dx.doi.org/10.1016/j.envdev.2011.12.005.

Meynard, J.-M., Cerf, M., Guichard, L., Jeuffroy, M.-H., Makowski, D., 2002. Which decision support tools for the environmental management of nitrogen? Agronomie 22, 817–829. http://dx.doi.org/10.1051/agro:2002064.

Mu, W., van Middelaar, C.E., Bloemhof, J.M., Oenema, J., de Boer, I.J.M., 2016. Nutrient balance at chain level: a valuable approach to benchmark nutrient losses of milk production systems. J. Clean. Prod. 112, 2419–2428. http://dx.doi.org/10.1016/j.jclepro.2015.09.116.

Oenema, O., Kros, H., de Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20, 3–16. http://dx.doi.org/10.1016/S1161-0301(03)00067-4.

Prost, L., Cerf, M., Jeuffroy, M.-H., 2012. Lack of consideration for end-users during the design of agronomic models. A review. Agron. Sustain. Dev. 32, 581–594. http://dx.doi.org/10.1007/s13593-011-0059-4.

Rasmussen, L.V., Bierbaum, R., Oldekop, J.A., Agrawal, A., 2017. Bridging the practitioner-researcher divide: indicators to track environmental, economic, and sociocultural sustainability of agricultural commodity production. Glob. Environ. Chang. 42, 33–46. http://dx.doi.org/10.1016/j.gloenvcha.2016.12.001.

Regan, J., Godinot, O., Nesme, T., 2016. Evidence of rebound effect in agriculture: recoupling crops and livestock at the discrit scale does not always reduce nitrogen losses. In: Aspects of Applied Biology 133. Presented at the ESA14 - Growing Landscapes - Cultivating Innovative Agricultural Systems. Association of Applied Biologists, Edinburgh, Scotland, pp. 8.1–8.2.

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: towards effective design and delivery. Agric. Syst. 149, 165–174. http://dx.doi.org/10.1016/j.agsy.2016.09.009.

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. http://dx.doi.org/10.1016/S1161-0301(03)00070-4.

Serrat-Capdevila, A., Valdes, J.B., Gupta, H.V., 2011. Decision support systems in water resources planning and management: stakeholder participation and the sustainable path to science-based decision making. In: Jao, C. (Ed.), Efficient Decision Support Systems - Practice and Challenges From Current to Future. InTech, Rijeka, Croatia, pp. 423–440.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347. http://dx.doi.org/10.1126/science.1259855.

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., Howard, C.M., Bleeker, A., Datta, A., 2013. The global nutrient challenge: from science to public engagement. Environ. Dev. 6, 80–85. http://dx.doi.org/10.1016/j.envdev.2013.03.003.

Uwizeye, A., Gerber, P.J., Schulte, R.P.O., de Boer, I.J.M., 2016. A comprehensive framework to assess the sustainability of nutrient use in global livestock supply chains. J. Clean. Prod. 129, 647–658. http://dx.doi.org/10.1016/j.jclepro.2016.03.108.

Watson, C.A., 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. Agroecosyst. 53, 259–267. http://dx.doi.org/10.1023/A:1009793120577.

Wheeler, D.M., Ledgard, S.F., Monaghan, R.M., McDowell, R.W., de Klein, C.A.M., 2006. Overseer nutrient budget model - what it is, what it does. In: Currie, L.D., Hanly, J.A. (Eds.), Implementing Sustainable Nutrient Management Strategies in Agriculture, Occasional Report. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand, pp. 231–236.

Yost, R., Attanandana, T., Colfer, C.J.P., Itoga, S., 2011. Decision support systems in agriculture: some successes and a bright future. In: Jao, C. (Ed.), Efficient Decision Support Systems - Practice and Challenges From Current to Future. InTech, Rijeka, Croatia, pp. 291–330.