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Benchmarking nutrient use efficiency of dairy farms: The effect of epistemic uncertainty

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ABSTRACT

The nutrient use efficiency (NUE) of a system, generally computed as the amount of nutrients in valuable outputs over the amount of nutrients in all inputs, is commonly used to benchmark the environmental performance of dairy farms. Benchmarking the NUE of farms, however, may lead to biased conclusions because of differences in major decisive characteristics between farms, such as soil type and production intensity, and because of epistemic uncertainty of input parameters caused by errors in measurement devices or observations. This study aimed to benchmark the nitrogen use efficiency (NUE_N; calculated as N output per unit of N input) of farm clusters with similar characteristics while including epistemic uncertainty, using Monte Carlo simulation. Subsequently, the uncertainty of the parameters explaining most of the output variance was reduced to examine if this would improve benchmarking results. Farms in cluster 1 (n = 15) were located on sandy soils and farms in cluster 2 (n = 17) on loamy soils. Cluster 1 farms were more intensive in terms of milk production per hectare and per cow, had less grazing hours, and fed more concentrates compared to farms in cluster 2. The mean NUE_N of farm in cluster 1 was 43%, while in cluster 2 it was 26%. Input parameters that explained most of the output variance differed between clusters. For cluster 1, input of feed and output of roughage were most important, whereas for cluster 2, the input of mineral fertilizer (or fixation) was most important. For both clusters, the output of milk was relatively important. Including the epistemic uncertainty of input parameters showed that only 37% of the farms in cluster 1 (out of 105 mutual comparisons) differed significantly in terms of their NUE_N, whereas in cluster 2 this was 82% (out of 120 comparisons). Therefore, benchmarking NUE_N of farms in cluster 1 was no longer possible, whereas farms in cluster 2 could still be ranked when uncertainty was included. After reducing the uncertainties of the most important parameters, 72% of the farms in cluster 1 differed significantly in terms of their NUE_N, and in cluster 2 this was 87%. Results indicate that reducing epistemic uncertainty of input parameters can significantly improve benchmarking results. The method presented in this study, therefore, can be used to draw more reliable conclusions regarding benchmarking the NUE of farms, and to identify the parameters that require more precision to do so.

1. Introduction

Nitrogen (N) is an essential nutrient for milk production. The input of N into European milk production systems has increased in the past decades, mainly via purchase of fertilizer and feed, but also via atmospheric deposition and biological fixation (Powell et al., 2010). These increased N inputs have also increased N losses to the environment, via leaching of nitrate (NO_3^-) and emissions of N-gases, such as nitrous oxide (N_2O) and ammonia (NH_3). These N losses contribute to environmental problems, such as eutrophication, acidification and global warming (Whitehead, 1995; Smith et al., 1999). To tackle this problem, the European Union introduced legislation, such as the Nitrates Directive (EU, 2006), which set limits on N application per hectare to reduce NO_3^- leaching.

There have been on-going studies and discussions on how to reduce N losses of dairy farms in Europe (e.g. Aarts et al., 1992; Schröder et al., 2003; Nevens et al., 2006; Phuong et al., 2013; Mihailescu et al., 2015). Calculating the nutrient balance at farm level is the most commonly used approach to evaluate these losses. In the Netherlands, for example, dairy farms are obliged to quantify their annual nitrogen and

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phosphorus balance from 2016 onwards (Veeteelt, 2015). A nutrient balance reflects the difference in nutrients entering and leaving a system, and allows computation of environmental indicators, such as the nutrient use efficiency (NUE) or the nutrient surplus per ha of a farming system (Spears et al., 2003). NUE generally is computed as the amount of nutrients in valuable outputs of a system over the amount of nutrients in all inputs of that system (Nevens et al., 2006).

Due to the simplicity of the method and relatively low data requirement, the nutrient balance has been used as a tool to benchmark the environmental performance of farms (Oenema et al., 2003; Schröder et al., 2003). Benchmarking is defined by Camp (1989) as "the search for those best practices that will lead to the superior performance" and, in this study, relates to the comparison of farms based on their environmental performance in order to identify differences and potentially, improvement options. Benchmarking farms based on, for example, their NUE, however, may lead to biased conclusions because of two reasons. First, as pointed out by Schröder et al. (2003), comparing the NUE of farms is justified only if they have similar major decisive characteristics. These characteristics can be based on: (unmanageable) physical factors, such as soil type and climatic conditions (Roberts, 2008; Powell et al., 2010); and long term strategic decisions, such as the degree of self-sufficiency (e.g. grass-based versus concentrate-based), production intensity, or manure management system (Nevens et al., 2006). Other characteristics that have an influence of the NUE of a farm include short term tactical decisions, such as choice of the feed crop, or grazing regime; operational decisions (i.e., day to day decisions); and other management skills of the farmer, such as the capacity to reduce losses (e.g. losses of feed, nutrients, milk or cows (culling)) (Nevens et al., 2006). Benchmarking NUE of farms should be based on differences in short term strategic and tactical decision-making, rather than differences in physical factors and long term decisions. Second, comparing NUE of farms may be affected by epistemic uncertainty of input data, caused by errors in measurement devices or errors around observations. Epistemic uncertainty can arise from e.g. errors in practically determining the N fixation by clover, measurement errors around the feed intake of the cows or estimations around the N-content of the animals (Oenema et al., 2015). Increasing knowledge or better measurements can reduce epistemic uncertainty (Walker et al., 2003; Groen et al., 2016).

Previous studies focused on examining the epistemic uncertainties of nutrient flows by looking into e.g. quantity of nutrient inputs (Mulier et al., 2003; Gourley et al., 2012; Oenema et al., 2015). However, they did not examine the impact of epistemic uncertainties on benchmarking results, nor did they benchmark farms with similar decisive farm characteristics.

The objectives of this study were to benchmark the nutrient losses by comparing nitrogen use efficiency (NUE_N) of farms with similar decisive characteristics while including epistemic uncertainty, and to examine which input parameters explain most uncertainty of NUE_N results. In addition, the epistemic uncertainties of input parameters that explain most of the output variance were reduced, to illustrate how this will improve benchmarking results.

2. Materials and methods

2.1. Case study: European specialized dairy farms

We used data of specialized dairy farms from Dairyman. Dairyman was a project directed at improving regional prosperity through better resource utilization on 113 dairy farms in different European countries (Dairyman, 2010). From the 113 farms, 32 specialized dairy farms were selected. Specialized dairy farms were defined as farms that have < 5% non-dairy purpose animals, and < 10% of their agricultural area in use for non-dairy purpose activities. These 32 dairy farms were located in different countries and regions (i.e. Netherlands (7), Ireland (13), Belgium (Flanders 8, Wallonia 2), Germany (1) and Luxembourg (1)).

Table 1
Characteristics of the 32 European specialized dairy farms used in this study.

Characteristics	Unit	Mean	Minimum	Maximum
Agricultural area	ha	65	25	270
Herd size	number of dairy cows	90	37	384
Milk production	kg milk cow^{-1} $year^{-1}$	7689	5700	9853
Milk production	kg milk ha^{-1} $year^{-1}$	12,598	3448	26,300
Grazing hours	h $year^{-1}$	2857	0	5146
Concentrate usage	kg cow^{-1} $year^{-1}$	1215	317	2459

Selected dairy farms differed in soil types (i.e. sandy soil, loam soil), milk production (i.e. milk production per cow and per ha), grazing hours per year, and feed import (i.e. kg concentrate usage per cow per year; Table 1). Whereas data on soil type, milk production and feed import were based on measured farm data, data on grazing hours per year were based on estimations by the farmers. Farm data from the year 2010 were used as baseline values to determine all N-flows.

2.2. Defining homogenous farm clusters

To enable benchmarking of NUE_N of farms with similar characteristics, farms were sorted into homogenous groups (i.e. typologies) based on their characteristics (Table 1). For this purpose, we used a two-step cluster analysis, because it allows using both continuous and categorical variables as clustering criteria (Chiu et al., 2001). To perform a cluster analysis with n criteria, a sample size of 2^n farms is required (Formann, 1984). Since our sample size included 32 farms, we selected 5 criteria for the cluster analysis, namely grazing hours, soil type, concentrate per cow per year, milk production per cow per year and milk production per ha (De Vries et al., 2015; Daatselaar et al., 2015). The analysis was performed in the statistical software package IBM SPSS statistics 22 (SPSS, 2015).

2.3. System boundary and model assumptions of calculating NUE_N

The NUE_N was quantified at farm level, implying that only on-farm flows and losses were considered. The N-flows through a dairy farm included in this study are visualized in Fig. 1. Inputs of N include N in mineral fertilizers, manure, animals, concentrates, roughages, biological N fixation and atmospheric N deposition. Outputs of N include N in animals, milk, manure and roughage. Stock changes (defined as final stock minus initial stock) of the mineral fertilizers, manure, animals, concentrates and roughages were taken into consideration during the computation processes. Manure output was subtracted from the total fertilizer input (i.e. through mineral fertilizer and manure). If the total manure output of the farm exceeded its total fertilizer input, excessive manure was treated as a loss. The internal N-flow from crop production to feed storage was based on the energy requirements of the herd, minus feed input and stock changes of feed. The calculation rules are specified in the Supplementary material. Losses of N from manure storage were based on storage type (i.e. slurry, solid) and the baseline values of manure N in all calculations (EEA, 2013).

2.4. Matrix based calculation for on-farm NUE_N

We used the matrix-based approach developed by Suh and Yee (2011) to quantify the N-efficiency of the 32 dairy farms. This approach was used to describe the herd and crop balance (Fig. 1) in one equation, which facilitates the global sensitivity analysis to examine epistemic uncertainty. A matrix-based approach allows for the presence of loops and parallel components, as is often the case on dairy farms (e.g. manure is used for the production of feed crops, which are consequently fed to the animals, producing manure). This approach requires a detailed insight into the nutrient flows within the farm.

The difference between the matrix-based approach to assess the