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Abstract

Agricultural production is often accompanied by nitrogen (N) losses causing negative environmental effects. In order to assess dairy farms´ N management, appropriate indicators based on robust farm data need to be addressed. This study investigated N balance and N use efficiency (NUE) as a function of grazing intensity on specialized dairy farms in northwestern Germany. For that, 30 farms were grouped according to pasture management from full grazing to zero grazing: >10 h in group 1, 6 to 10 h in group 2, <6 h in group 3, and group 4 without pasture access. Based on multiple farm data, substance flow analysis was carried out. Subsequently, the data were analyzed according to the relevant indicators N surplus and NUE on feed-, field- and farm-level. The results revealed N surpluses on all farms, with the average N surplus tending to decrease from 259 to 179 kg N ha^{-1}, and farm-NUE to increase from 40 to 50 %, from full grazing to zero grazing management systems. There were considerable differences between the N balances calculated in this study and those reported by farms as part of statutory net N soil surface balance reporting under the German regulatory law. In conclusion, the N indicators were suitable to compare farm performance among and within different dairy farming systems. When comparing indicator values there is a need to consider the methodology applied, the system boundaries set, and the origin and quality of data used.

List of abbreviations

ATD	Atmospheric deposition
BNF	Biological nitrogen fixation
CP	Crude protein
DC	Dairy cattle
DüV	Düngeverordnung (Fertilizer Application Ordinance)
ECJ	European Court of Justice
ECM	Energy-corrected milk
IRR	Internal Roughage Recording
LSU	Livestock unit
N	Nitrogen
NutC	Nutrient Comparison
NH_3	Ammonia
NO_3^-	Nitrate
NUE	Nitrogen use efficiency
SFA	Substance flow analysis
StoffBilV	Stoffstrombilanzverordnung (Ordinance on Substance Flow Analysis)
UAA	Utilized agricultural area

1. Introduction

1.1. Problem

Nitrogen (N) is an essential nutrient in agricultural production and its use has intensified in recent decades, to meet growing global food needs. However, overuse of N fertilizers in some regions has led to various environmental problems (FAO 2018). Since N appears in environmental media (i.e., air, water, and soil) in different reactive forms, it has multiple impacts. Gaseous N compounds can have negative effects on air quality and climate warming, while nitrate mobilized through leaching and run-off impairs water quality. The latter leads to high nutrient accumulation in soils and waters (eutrophication), e.g. due to inadequate application of manure, which poses a serious environmental hazard (Fields 2004, Leip *et al* 2015). Eutrophication due to increased emissions of nitrate and phosphate results mainly from nutrient surpluses in agriculture (Leip *et al* 2015, SRU 2015, Jansson *et al* 2019).

The anthropogenic influence on the N cycle is primarily related to production and use of N fertilizers for agriculture, with atmospheric molecular unreactive N in the order of 120 million tons being converted annually into reactive forms such as ammonium, nitrate, and nitrous oxide in the early 2000s (Rockström *et al* 2009a). Nitrogen is defined as one of three 'planetary boundaries', along with climate change and biodiversity loss, for which the tolerable limits are being exceeded (Rockström *et al* 2009b). Therefore, there is a need to apply organic and mineral N fertilizers in a more efficient and sustainable way, in order to produce sufficient food while reducing negative environmental impacts (The Federal Government 2016).

Agriculture in western and northwestern Germany is characterized by high livestock numbers per hectare (ha), with high N surpluses that often result in the legal nitrate threshold values in groundwater being exceeded (LWK Nordrhein-Westfalen 2018, Meergans and Lenschow 2018, LWK Niedersachsen 2019). Lower Saxony is one such region, with intensive dairy production resulting in high application rates of manure, e.g., 175 kg N ha^{-1} annually in the administrative district of *Weser-Ems* (Neuenfeldt and Gocht 2017, LWK Niedersachsen 2019 based on Gocht and Röder 2014). Due to subsidies for renewable energy (BMWi 2017), biogas facilities have also expanded in the region, using energy crops such as maize and manure as the main substrates. Nutrient-rich digestate is returned to neighboring fields, since digestate and/or manure transport is usually not cost-effective (Schindler 2009). Dairy farming in Lower Saxony was traditionally based on pasture grazing during summer (Schaak and Musshoff 2018), but the pasture area has been declining (DESTATIS 2019). Large farms now commonly apply zero grazing, while the number of dairy farms with integrated pasture management is decreasing (Neuenfeldt *et al* 2019).

1.2. Legal background

Legal requirements at national and international level have been introduced to reduce N losses from agriculture, sustain long-term food security, and ensure the same standard of living for future generations (*intergenerational equity*). These are in compliance with national and international environmental objectives, i.e., improving water quality, reducing ammonia emissions, and combating climate change (De Vries *et al* 2013, SRU 2015).

To this end, the European Union (EU) Nitrates Directive aims to reduce and prevent further pollution of waters caused by nitrates from agriculture, in particular through fertilization, by promoting the use of 'good farming practices' (European Council 1991). Under the directive, EU Member States are obliged to draw up national four-year action programs to reduce nitrate pollution (European Commission 2019).

The upper limit for groundwater (50 mg NO_3^- L^{-1}) defined in the Nitrates Directive has been exceeded at many monitoring sites in recent decades. Therefore, an infringement procedure against Germany was launched in 2013 (Salomon *et al* 2015) and resulted in a conviction in June 2018 (ECJ 2018). Following an inadequate amendment in 2017 (Kuhn *et al* 2020), efforts to comply with the Nitrates Directive led to tightening of the German Fertilizer Application Ordinance (Düngeverordnung, DüV) in 2020. It also led to abolition of Nutrient Comparison (NutC), a soil surface N and P balance reporting which had been obligatory since 1996 in Germany. Due to shortcomings of this balance approach, a farm-gate balance was introduced in 2018 through the Ordinance on Substance Flow Analysis (Stoffstrombilanzverordnung, StoffBilV). However, StoffBilV has not been part of Germany's action program to comply with the EU Nitrates Directive, but it was initiated in order to achieve the target for sustainable nitrogen management of the German Sustainable Development Strategy (The Federal Government 2016, StoffBilV 2017).

1.3. Indicators for evaluation of N balances

Agri-environmental indicators are characteristic numbers for estimating the environmental impact of agricultural production systems (EEA 2005, OECD 2013, Eurostat 2017). These are used: (1) for national and international reporting, (2) as determining factors for agri-environmental policy measures, (3) in the context of voluntary single-farm environmental information systems, and (4) to inform the broader public by illustrating agri-environmental relationships (Eurostat 2017). Different countries use differing methodologies for calculating these indicators (Klages *et al* 2020). This should be considered when setting indicative target values, which can lead to challenges in terms of national and cross-country comparability of reference or benchmark values (Eurostat 2018).

The nutrient balance of a farm is a relevant indicator for analysis of nutrient management. Agricultural nutrient balances can be distinguished according to the system boundary (e.g., farm-gate, soil surface), the nutrients they include (e.g., phosphorus or N), and whether N emissions from volatilization in animal stables, manure storage, and manure application to soil are excluded (*net balance*) or included (*gross balance*) (Eurostat 2013). The surplus/deficit identified through comparison of all inputs and outputs for a farm or agricultural sector represents the potential threat to the environment and the supply of nutrients to the soil (Eurostat 2019a).

Nitrogen use efficiency (NUE) is another key parameter used for evaluation of farm nutrient balance, as an indicator of resource use efficiency. It is calculated as total N removals over total N inputs and provides an indication of e.g., kilograms (kg) N incorporated into crop products per kg N input (PARCOM 1993, UNECE 2014). Production system, technologies, type and level of management have a strong influence on both N balance and NUE (Leip *et al* 2011, Eurostat 2018). As N surpluses are particularly high in intensive livestock farming areas, these regions are often the main target of efforts to increase NUE (Arriaga *et al* 2009, Gourley *et al* 2011b, Kanter *et al* 2020).

According to Powell *et al* (2010), NUE can be determined on three levels; (a) feed conversion (feed-NUE), (b) manure and fertilizer conversion into crops and pasture (field-NUE), and (c) farm-NUE, defined as the ratio between N exports (sold milk, crops, animals, losses leaving the farm) and N imports (feed, fertilizer, atmospheric deposition (ATD), biological N fixation (BNF)).

Substance flow analysis (SFA) is used for quantifying mass flows and for assessing nutrient fluxes through agricultural systems. SFA is based on input-output flows of every process along the supply chain, and processes connected to each other within the system. Thus the approach is useful for identifying 'hotspots' of nutrient losses within the on-farm N cycle, as it provides information about the type and extent of losses (environmental pressure), but not about impacts on the environment (Gerber *et al* 2014). In order to generate an SFA, large amounts of accurate data are required, which are often not available or accessible on farm scale. Assumptions can be useful, but they make the result less precise and relevant. Thus, due to the time and data requirements, SFA can be difficult to apply.

1.4. Research gap

There is copious national and international literature focusing on nutrient balances and NUE of dairy farms. Nutrient balancing in agriculture at different reference levels (e.g., soil, farm) has been in the scientific spotlight for decades (e.g., Harenz *et al* 1992, Bach *et al* 1997). Research regarding N balance and NUE at *farm* level and its meaning for agricultural and political actors is described by Powell *et al* (2010), Velthof *et al* (2009), Oenema *et al* (2003), and others. Feeding studies have found that ratio of roughage and concentrates has effects on NUE (Velthof *et al* 2009, Akert *et al* 2020), specifically through affecting milk production (Shortall *et al* 2017), and the amount of manure (Castillo *et al* 2000, Baron *et al* 2002, Arriaga *et al* 2009). Gourley *et al* (2011a) investigated contrasting dairy production systems and the impact on feed-NUE in different regions in Australia and found generally lower NUE on grazing-based dairy farms. For farm-NUE, temporal differentiation in pasture management has not been considered in previous studies (Scheringer 2002, Gourley *et al* 2011b). Thus there is a knowledge gap regarding farm-NUE of dairy farms with similar operating structures, but different pasture management systems, in intensive grassland regions.

1.5. Objectives and overall research approach

The overall aim of the present study was to compare N surpluses and NUE on dairy farms with different grazing systems in northwestern Germany and assess whether the data source affected the results. For livestock farms in particular, analysis of possible N flows at single farm level is of major relevance for identifying the potential for improving efficiency. Thus, key variables were investigated to identify interdependencies between NUE and grazing intensity. Dairy farms in Lower Saxony were selected for the study on the basis of similar farm structure and being located in the same region, to ensure similar environmental factors, e.g., soil type and climate. Pasture management systems on the farms ranged from highly intensive (full) grazing to zero grazing, and their potential for sustainable management of limited resources was compared. In this context, an attempt was made to link the comparison of farm-NUE with SFA based on (1) comprehensive farm data and (2) multiple sets of information obtained from different data sources, in order to cope with data implausibilities and to identify potential N inefficiencies. The overall intention was to make recommendations for actions by political actors designing environmental protection measures. Therefore, the following hypotheses were formulated:

H1. NUE and total N balance differs according to the grazing system.

H2. Different data qualities need plausibility checks in order to obtain robust and reliable results on analyses of NUE and total N balance.

2. Material and methods

2.1. Data

The farm data used in the study were obtained from a joint research project funded by the Federal State of Lower Saxony with the collaboration of eight national scientific, advisory and administrative institutions, which analyzed dairy production systems in that region between 2013 and 2018. The project focused on comparison of zero grazing and several pasture management systems on a total of 63 conventional full-time dairy farms. Farm selection was conducted with the help of the Chamber of Agriculture of Lower Saxony, whereas cubicle housing, a minimum herd size of 60 *Holstein-Friesian* or *Red-Holstein* dairy cows, and participation at routine herd data recording were the selection criteria. From around 10,700 dairy farms in Lower Saxony where approximately 60% having a minimum herd size of 60 cows in year 2015 (DESTATIS 2020), a total of 80 farms met the selection criteria of the project and were asked by the Chamber of Agriculture to participate, resulting in 63 farms to be willing. All these were located in the intensive grassland regions of Lower Saxony (Isselstein *et al* 2018, Armbrecht *et al* 2019).Long-term mean annual air temperature and precipitation throughout the region are 8.6 °C and 745 mm, respectively (DWD 2018). The dominant soil types are sandy soils and heavy loams in inland parts and clay soils in coastal areas (Roßberg *et al* 2007). Application rate of organic and organo-mineral N fertilizer is slightly below the threshold value of 170 kg N ha^{-1} a^{-1} stipulated in DüV, e.g., in Leer county, in which four farms are located, the mean application rate was 164 kg N ha^{-1} a^{-1} in 2018 (LWK Niedersachsen 2019).

Detailed descriptions of the farms, the regional structure of dairy farming, and methods of data acquisition for the project can be found in Armbrecht *et al* (2019), Hartwiger *et al* (2018), and Isselstein *et al* (2018). As a basis for calculations in the project, the following data were acquired from the farms, supported by on-site visits 2013–2016, which were documented in varying degrees of completeness:

- Monthly milk performance and quality data, providing data on milk production and its nutritional value
- Annual nutrient balances (according to Article 8 of DüV), providing data on manure and mineral fertilizer application volume, harvested quantities, and other parameters for the calendar year (January-December), crop/fiscal year (July-June), or forage year (May-April)
- Animal traceability and information system, providing animal data
- Multi-year seasonal on-farm feed rations recordings collected by the Chamber of Agriculture of Lower Saxony, providing data on feed composition and nutritional value
- Delivery notes for purchased feeds
- Internal Roughage Recording (IRR), providing farm-individual data on actual roughage quantities harvested, stored and utilized, and verified by the Chamber of Agriculture
- Data from the Integrated Administration and Control System on arable land, cultivated crops, grassland and livestock numbers.

In the present study, project farms for which data for the selected reference year (2014) were incomplete were excluded, resulting in a total of 30 dairy farms. In terms of dairy farm type, the sample included 12 grassland farms and 18 forage production farms, based on a classification relating to proportion of grassland (LfL 2018a). The farms were divided into the following four groups, based on grazing intensity on pasture:

- Group 1 ($n = 7$): full grazing system, with more than 10 h daily grazing
- Group 2 ($n = 8$): half-day grazing system, with 6–10 h daily grazing
- Group 3 ($n = 10$): part-time grazing system, with up to 6 h daily grazing
- Group 4 ($n = 5$): year-round indoor system, zero grazing.

Pasture access is provided for at least 120 days per year on farms in groups 1–3. Nitrogen balance was calculated using farm data on number of cattle, milk yield, roughage production, grazing time, purchased feed concentrates, and use of N fertilizers. Input and output flows were then calculated for each farm as required by StoffBilV (2017) and DüV (2017), following the approach proposed by Schüler *et al* (2016).

Table 1 gives an overview of all farms in the different groups. Farm structure information, such as proportion of grassland in total agricultural land and characteristics related to livestock farming, is also shown.[1]

2.2. Substance flow analysis

2.2.1. System boundary

The observed N flows at farm level were linked to the methodology of farm-gate balancing (e.g., Nevens *et al* 2005, Machmüller and Sundrum 2016) defined in StoffBilV (2017), with additional consideration of internal N flows (e.g., roughage, manure). The farm-gate balance refers to the farm boundaries and records N in all products that enter and leave the farm. Gross farm-gate balance according to StoffBilV (2017) was calculated by grouping the N flows as follows:

Inputs: Fertilizers (manure of animal origin, other organic fertilizers, mineral fertilizers), soil additives, growth media, feedstuffs, seeds including plant material, purchase of animals, BNF, ATD, other substances.

Outputs: Plant products, animal products, fertilizers (manure of animal origin, other organic fertilizers, mineral fertilizers), soil additives, growth media, feedstuff, seeds including plant material, dead animals, other substances.

As a gross balance calculation was conducted, factors for losses from manure volatilization in animal stables, in storage, and during application to soil were considered according to DüV (2017), in order to analyze the entire nutrient flows and to allow for comparison with NutC parameters.

Losses: Standard factors for losses due to N emissions from semi-liquid indoor manure according to DüV (2017) from (a) volatilization in stables and storage (15%) and (b) manure application to soil (15%) and (c) total N emissions from animal excretions on pasture (75%).

2.2.2. Calculation of N flows

The N surplus and NUE of the different groups of farms, and the variation within the groups, were analyzed. By comparing the inputs (manure, mineral N fertilizers, etc), outputs (milk, meat, etc) and other relevant parameters (plant uptake, storage losses, yield losses) of the 30 dairy farms in the sample, surpluses were quantified and inefficiencies in substance flows were identified. SFA was carried out to assess NUE, assuming N flows in 'Boxes 1–7' below, following the approach in Schüler *et al* (2016), with certain modifications. These included (a) manure N losses, in compliance with the regulatory framework in Germany, (b) 'stocks', in order to more accurately reflect actual roughage management; and (c) factor-based pasture uptake, avoiding the approach of derivation based on energy balance due to need-based inputs of roughage, and concentrates. Alternatively, the pasture uptake derived from energy requirements and actual feed rations can lead to inhomogeneous up to negative uptake rates and thus to incorrect assumptions, as over-consumption of feed and forage is not depicted in a strictly need-based estimation.

In the following, we describe the subsystems ('boxes') of the SFA as illustrated in figure 1.

2.2.2.1. Box 1 Crop production

Box 1 quantified N inputs entering the field and N outputs leaving the field. The N inputs to this box were farm-produced and imported manure, mineral fertilizer, ATD, and BNF. The N outputs were plant products for export (cash crops), and roughage (maize and grass remaining in the farm system).

The N quantities removed by cash crops and roughage were subtracted from the sum of N quantities applied in fertilizers. The annual quantities in excreta used as manure (feces, urine, litter) and the corresponding N concentrations were taken from the internal obligatory nutrient balance reports in NutC (Under Article 8 of DüV 2017) as well as the quantities of purchased mineral fertilizers and BNF. For ATD, an additional region-specific input of 20 kg N ha^{-1} was included in the calculation, as required by StoffBilV (2017) and UBA (2019). The N quantities and qualities harvested in cash crops and roughage were also taken from NutC. Manure N quantities from pasturing were deduced from the proportion of gross manure entering the 'pasture system' and utilized as 'pasture fed', as a function of the grazing intensity in hours and herd size. Manure N losses of 75% on pasture according to DüV (2017) were taken into consideration. Thus, balance 1 provided information on the amount of N not used by crops, and remaining in the soil or lost in the neighboring environment (equation (1)):

[1] A livestock unit (LSU) equal to 500 kg living biomass. A conversion factor from DüV (2017) was used to determine the number of LSU: a dairy cattle or heifer is 1 LSU, a young cattle (1-2 years old) is 0.7 LSU, and a calf (up to 1 year old) is 0.3 LSU. Since other age limits were used in the present study, a mean value of 0.5 LSU was used for a calf (up to 1.5 years old) 0.85 LSU for a heifer (from 1.5 years old up to the first calving). Calves and heifers were grouped as 'young cattle' in the study.

Table 1. Farm-specific data on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing) for the reference year 2014.

		Utilized agricultural area [ha]	Grassland [% of UAA][a]	Grazing time [hours/DC/a]	Dairy cattle	Young cattle	Milk yield [kg ECM/DC/a]	Milk protein [%][b]	Livestock units	Area-related LSU [LSU/ha UAA]
Group 1	Mean	108	69	3 177	125	106	8741	3.39	189	1.7
(n = 7)	Min–max	68–178	24–97	2430–4000	64–225	45–171	6334–9964	3.32–3.50	106–337	1.4–2.2
	SD	42	31	587	56	44	1146	0.08	84	0.3
	Median	86	86	3 233	116	105	9028	3.34	178	1.7
Group 2	Mean	117	81	1 706	121	131	8657	3.40	199	1.8
(n = 8)	Min–max	65–243	62–100	1556–1978	83–229	80–233	7549–10228	3.36–3.52	131–356	1.3–2.2
	SD	57	17	172	46	58	846	0.05	72	0.3
	Median	102	78	1 617	105	105	8443	3.38	169	1.8
Group 3	Mean	118	71	1 276	129	136	8874	3.34	209	1.9
(n = 10)	Min–max	57–245	41–95	1048–1464	88–215	57–330	7312–10383	3.19–3.48	122–408	1.1–2.2
	SD	55	15	146	37	74	1014	0.08	79	0.3
	Median	103	71	1241	122	126	8587	3.33	197	1.9
Group 4	Mean	118	51	24	182	119	9180	3.42	251	2.2
(n = 5)	Min–max	89–143	26–72	0–120	100–263	0–205	6789–10209	3.38–3.47	167–382	1.2–3.0
	SD	20	17	54	69	76	1372	0.04	79	0.7
	Median	120	53	0	158	118	9695	3.41	238	2.0

UAA = utilized agricultural area; DC = dairy cattle; ECM = energy-corrected milk; LSU = livestock unit.

[a] According to interviews with farmers, alternatively from *Agricultural Aid Lower Saxony Digital.*

[b] Three farms with average values of the study sample.

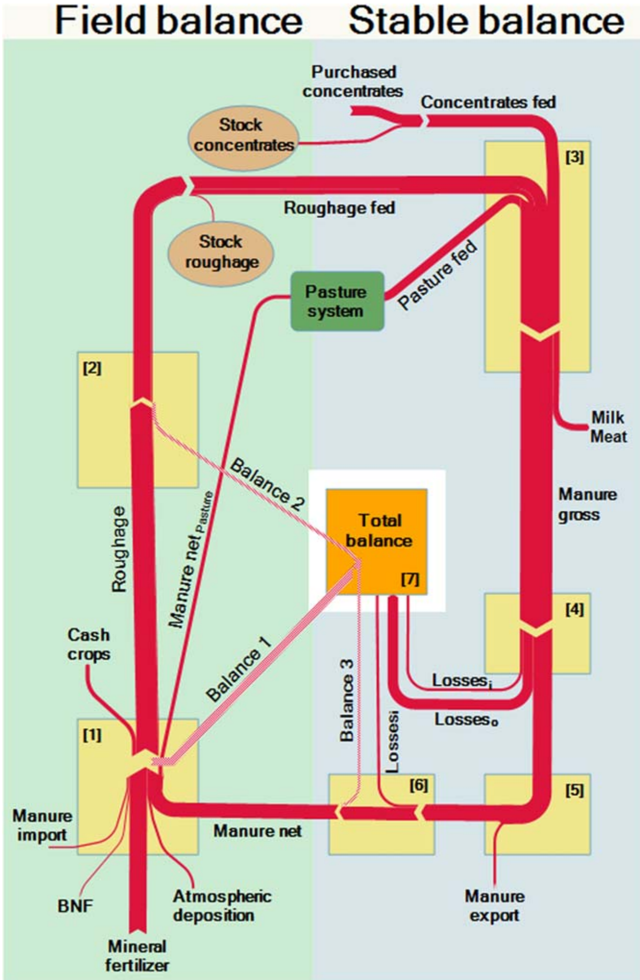

Figure 1. Example of nitrogen flow analysis for a dairy farm. Boxes 1–7 indicate points of even mass balances for nitrogen (own design following the sample representation in Schüler *et al* 2016).

$$\begin{aligned} Balance\ 1 = \ & Mineral\ fertilizer\ N + Manure\ N_{NutC}[total\ net] \\ & + Legumes\ N + Atmosphere\ N - Harvest\ N\ sold \\ & - Roughage\ N - Manure\ N\ _{NutC}[outdoor\ net] \end{aligned} \tag{1}$$

2.2.2.2. Box 2 Roughage storage

For Box 2, two different approaches were used to document the N quantities removed by roughage. As N inputs, internal NutC records on N removals were used, including average roughage yields from previous years. As N outputs, the IRR assessment of actual annual N removals from roughage was used. Thus, balance 2 provided information on the difference between reported and estimated amount of N removed by roughage (equation (2)):

$$Balance\ 2 = Roughage\ N\ [NutC] - Roughage\ N\ [IRR] \tag{2}$$

2.2.2.3. Box 3 Feed storage and animal stable

Box 3 quantified N inputs entering and N outputs leaving the livestock production systems. The N inputs in this box were from concentrates, roughage, and pasture feed. The N outputs were manure, milk, and meat.

First, the daily intake of roughage per dairy cattle was calculated based on multi-year seasonal feed rations recordings, providing data on quantities and crude protein (CP) values. For CP, an N content of 6.25% was assumed (Gourley *et al* 2011a, Koesling *et al* 2017, Leip *et al* 2019). For young cattle (0–24 months), a factor for roughage intake of 0.3 compared with the daily intake of dairy cattle was used, which is in line with recommended values in GfE (2001), DüV (2017), and LfL (2018b). The feed ration per animal was then multiplied by the number of livestock and extrapolated to one year, resulting in total N uptake from roughage. This value was subtracted from the N quantities removed by roughage measured in IRR, giving the change in roughage feedstock.

Second, concentrated feed ration per dairy cattle and day was calculated based on the feed rations recordings. A factor for concentrated feed intake of 0.1 was assumed for young cattle, considering the average feed ration based on farm data. Total N uptake from concentrates was deduced from the year's rations recordings multiplied by the number of livestock. The resulting sum was subtracted from total N in annually purchased concentrates, giving the change in concentrate feedstock. This consideration of stocks is a further development of the methodology proposed by Schüler *et al* (2016), as the available feed quantities do not correspond to the actual rations fed.

Third, the N quantities removed by grazing were calculated, based on the on-farm annual grazing intensity in hours and assumed pasture uptake of 0.4 kg hr^{-1} (A. Lasar, personal communication, April 23, 2019), on the basis of assessments of animal nutrition by experts involved in the project. The dry matter quantity of pasture uptake per dairy cattle and year was interpolated by relating it to on-farm annual grazing hours. Finally, this amount was divided by the CP content of pasture (18.8%), and the figure obtained was divided by the N content of CP, resulting in total N uptake through pasture grazing (Hartwiger *et al* 2018). In a further step, this value was subtracted from the amount of manure on grazing land as shown in Box 1, indicating over- or undersupply of N on pasture.

Fourth, the total amounts of N needed for milk and meat production were added up and compared to total N uptake, with the deficit resulting in the amount of N from manure (equation (3)), following Osterburg and Schmidt (2008). For calculating annual milk production, on-farm daily milk production rate per dairy cattle was extrapolated to one year and dairy cattle herd. Again, this amount was divided by the measured on-farm CP content (min-max 3.19%-3.52%) and then divided by the N content of milk CP (6.38%) resulting in the total N output through milk production. For the increase in living biomass (meat production), a rate of weight increase of around 0.7 kg d^{-1} in young cattle was assumed (LfL 2018b). The N output due to meat production in young cattle was calculated by setting the CP content of meat at 20%. Therefore, all parameters needed in order to derive the total amount of manure N were known:

$$Manure\ N\ [gross] = Roughage\ N\ uptake + Concentrates\ N\ uptake + Grazing\ N\ uptake - Milk\ N + Meat\ N \quad (3)$$

2.2.2.4. Box 4 Manure storage

Box 4 quantified N losses due to volatilization in animal stables and storage. The N inputs to this box were from total gross manure, while the N outputs were manure and volatile losses in stables and storage. As different loss factors apply for manure from indoor housing or grazing, the time ratio indoors:pasture was calculated and applied to the total amount of manure. For grazing, total N losses were quantified at a flat rate of 75% according to DüV (2017). With regard to indoor housing, losses were quantified at a flat rate of 15% in accordance with StoffBilV (2017) and DüV (2017) and subtracted from Box 4, due to leaving the system. Thus, Box 4 provided an approximation of the amount of N from manure available after deduction of losses (equation (4)):

$$Manure\ N\,[storage] = (Manure\ N \times Ratio\ pasture \times N\ losses\ [outdoor]) + (Manure\ N \times Ratio\ indoor \times N\ losses\ [indoor_1] \quad (4)$$

2.2.2.5. Box 5 Export

Box 5 quantified N exports of manure. The N inputs to this box represented manure in storage, and the N outputs were from manure and exported manure quantities (equation (5)). If a farm exported manure, this N amount was subtracted from the previously determined manure N quantity.

$$Manure\ N\,[post\ export] = Manure\ N\ [storage] - Manure\ N\ [export] \quad (5)$$

2.2.2.6. Box 6 Manure application

Box 6 quantified N losses due to field application. The N inputs in this box were from manure and the N outputs were manure as reported in NutC and application losses quantified at a flat rate of 15%, in accordance with StoffBilV (2017) and DüV (2017), subtracted from *Manure N [post export]*, leaving the system. The result was the calculated amount of N from manure applied to the field (equation (6a)). In the next step, this amount was subtracted from the quantity of manure taken from NutC, where losses in stables, storage, and application were also considered. As a result, balance 3 provided information on the difference between the amount reported in obligatory documentation and the calculated amount of N from manure applied on the field (equation (6b)).

$$Manure\ N\,[net] = Manure\ N\,[post\ export] - Manure\ N\ [gross] \times Ratio\ indoor \times N\ losses\ [indoor_2] \quad (6a)$$

$$Balance\ 3 = Manure\ N[net] - Manure\ N_{NutC}[net] \tag{6b}$$

2.2.2.7. Box 7 Total N balance

Nitrogen losses were added together (equation (7)) by combining balances 1, 2, and 3 and adding losses. This resulted in on-farm total gross N balance, generally expressed in relation to area for better comparability, primarily per hectare of utilized agricultural area (UAA) (equation (8)). This approach can be applied in terms of the available data and internal flows depicted in figure 1. Otherwise, the general equation is shown in equation (9).

$$Losses = N\ Losses\ [outdoor] + N\ Losses\ [indoor_1] + N\ Losses\ [indoor_2] \tag{7}$$

$$Total\ N\ balance = Balance\ 1 + Balance\ 2 + Balance\ 3 + Losses \tag{8}$$

$$Total\ N\ balance = Purchased\ feed\ N\ intake + N\ fertilizer\ and\ manure\ import - Milk\ N - Meat\ N - Harvest\ N\ sold - Manure\ N\ soldexport \tag{9}$$

Figure 1 illustrates the methodological approach for SFA at farm scale applied in the present study. Rectangular boxes depict the N flows as defined above, circles are used to show stock changes for roughage and concentrates, and the rounded rectangle depicts the 'pasture system'. Balances are presented as scattered lines indicating N surpluses.

2.3. Nitrogen use efficiency

NUE was calculated at different levels (feed, field, farm). NUE is generally defined as N output divided by N inputs. The NUE at different levels was calculated as follows:

$$Feed - NUE\ [\%] = 100 \times \frac{Milk\ N\ [g\ DC^{-1}\ d^{-1}]}{Feed\ N\ intake\ [g\ DC^{-1} d^{-1}]} \tag{10}$$

Feed-NUE (equation (10)): For better comparability, only milk N was included as an output in feed-NUE, following Powell *et al* (2010) and Gourley *et al* (2011a). This approach is preferable, since the feed composition of dairy cattle is more reliable than that for young cattle in different development stages. Feed rations may also vary during the year or over a period of time. In the present study, average on-farm feed rations for dairy cattle were calculated based on multi-year records on feed rations, assuming that animals on the same farm are fed similar feed rations throughout the year and over the years.

$$Field - NUE\ [\%] = 100 \times \frac{N\ uptake\ by\ crops\ [kg\ a^{-1}]}{N\ applied\ [kg\ a^{-1}]} \tag{11}$$

Field-NUE (equation (11)): Harvested N amounts were taken from IRR. As inputs, N in manure (calculated according to equation (3)), mineral fertilizer, and BNF were taken into consideration, following Powell *et al* (2010). Nitrogen from manure on pasture was subtracted beforehand from the total manure N pool. For this, the ratio of pasture time to indoor time was calculated based on internal documentation on pasture management, and related to the total amount of manure derived from on-farm feed rations and animal products sold (milk, meat). Additionally, harvested N and manure N amounts from two different data sources (IRR, NutC) were taken into consideration as variant calculations (cf 2.4).

$$Farm - NUE\ [\%] = 100 \times \frac{Milk\ N\ [kg\ a^{-1}] + Meat\ N\ [kg\ a^{-1}] + Harvest\ N\ sold\ [kg\ a^{-1}] + Manure\ N\ soldexport\ [kg\ a^{-1}]}{Purchased\ feed\ N\ intake\ [kg\ a^{-1}] + N\ import\ [kg\ a^{-1}]} \tag{12}$$

Farm-NUE (equation (12)): On farm level, total N exports were divided by total N imports. For exports, all animal products sold (milk, meat, manure) and plant products sold (total harvest N except grass and maize) were considered. In the denominator, the sum of N imports in feed, mineral fertilizer and manure was considered, as well as ATD and BNF. Here, purchased feed N intake was calculated from the average on-farm feed ration.

Since dairy farms are normally analyzed as a whole, farm-NUE was of particular interest in this study. However, feed-NUE and field-NUE provide important information for a better understanding of farm management structure and the implications for N use.

2.4. Plausibility check of N-related data

To obtain comprehensive and reliable data, different data sources for harvested N and manure N amounts were taken into consideration in this study. Declarations in the NutC were compared with IRR data, feed rations and estimated N uptake through pasture grazing, and calculated values for manure N using SFA equation (3).

N quantities in declared roughage yields are much higher in NutC compared to IRR values, ranging from 21% higher for group 4 to 105% higher for group 2. They also greatly exceeded the N amount fed according to farm-individual rations plus estimated pasture intake. This discrepancy is presumably because farmers report roughage yield as an approximation, rather than a precise measurement, since roughage is predominantly utilized within the farm and not sold. Also, roughage rests and losses, as well as stock changes, may explain the discrepancy between roughage yields and rations. Roughage rests are normally returned to crop- and grassland, however, these flows are not accounted for in NutC. Therefore, declared gross roughage yields are rather overestimated on average, leading to an overestimation of N outflows from the field.

Compared to NutC declarations according to DüV (2017), calculated N from manure based on SFA is similar for young cattle including calves (+1.6 kg N/LSU/year) and consistently higher for dairy cattle (+24.5 kg N/LSU/year), over different production systems. Farms in group 1, 2, and 4 showed predominantly higher SFA values compared to NutC, while the deviations for farms in group 3 were both positive and negative to a similar extent. Obviously, N in manure is often underestimated in the NutC declarations. Further, the relation of declared roughage yields and manure N in NutC is not balanced when applying SFA equation (3), which reflects the balance of N inputs and outputs in the livestock production system, and thus appears implausible.

Figure A1 is available online at stacks.iop.org/ERC/2/105002/mmedia depicts deviations between the aggregate of N in roughage ration plus N uptake through pasture grazing minus manure N according to SFA, and roughage N minus manure N according to NutC. The aggregate values are on average much lower for SFA compared to NutC, showing that NutC values systematically distort the relation of N inputs and outputs in the field balance, due to underestimated inputs and overestimated outputs of the field balance. NutC data on roughage and manure N thus are not reliable to calculate field-NUE. In table A1, results of an explorative calculation of field-NUE using NutC data with low data reliability, and SFA data with high data reliability are presented. Field-NUE values based on NutC are by orders of magnitude higher compared to those based on SFA data, with maximum values above 100% in farms with grazing, and also the ranking of field-NUE per farm group differs compared to results based on SFA. The example shows the importance of robust and reliable data for NUE calculations.

For the analysis of N balances and NUE, data from NutC on input of mineral fertilizers, purchase and sale of organic fertilizers, yields of cash crops, and number of livestock and land area are used, as well as information on milk production according to monthly milk performance tests. As a result of the plausibility check, instead of inconsistent NutC data, yearly on-farm feed rations collected by the Chamber of Agriculture, data on roughage production from IRR, and calculated N uptake through pasture grazing and manure N according to SFA and manure N according to SFA equation (3) are used for the analyses of N balances and NUE.

2.5. Statistical analysis

For explorative data analysis, mean and standard deviation according to group affiliation were calculated based on the corresponding functions in *Microsoft Excel Professional Plus 2010.* The software SAS (*SAS 9.4*), commercial statistics software, was used in statistical analyses for independency. Kruskal-Wallis one-way analysis of variance (ANOVA), also known as the Kruskal-Wallis test by ranks, was applied to mean values of farms in group 1 and group 4. This is a commonly used test to investigate whether more than two independent samples are significantly different.

3. Results and discussion

3.1. Farm structure

The 30 dairy farms in the sample differed in structure both between groups and within each group (see table 1). Across all farms, total agricultural land area was rather similar (115 ± 46 ha; mean ± standard deviation), with differences mainly in the relative proportions of arable land and grassland.

With regard to structural features such as livestock density, size/ratio of grassland and arable land, and herd size, the 30 selected farms in Lower Saxony represented the diverse range of production characteristics in dairy farming in the region. Livestock density across all farms ranged between 1.1 and 3.0 LSU ha^{-1} (1.9 ± 0.4 LSU ha^{-1}), with an average total number per farm of 135 ± 52 LSU. This is relatively high compared with the German average and the European average (1.1 and 0.8 LSU ha^{-1} UAA, respectively, in 2016) (Eurostat 2019b).

Under EU regulations on organic production and labeling of organic products, farms complying with organic production rules must keep livestock density below 2 LSU ha^{-1} in order to avoid exceeding the European threshold value for manure application of 170 kg ha^{-1} (European Commission 2008). For conventional farms, there is no area-related limitation on livestock density. For dairy farms in Germany, Scheringer (2002) found that organic farms have higher NUE than conventional farms and that extensification and organic farming are effective measures to reduce N surpluses and improve NUE. However, lower livestock

Table 2. Comparison of nitrogen (N) inputs and N outputs on field level on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing).

		N input [kg N/ha]					N output [kg N/ha]		
		Mineral fertilizer	Manure (gross)	Manure (net)[a]	Manure export	Manure import	Grass	Maize	Other crops[b]
Group 1	Mean	178	224	119	13	0.4	91	11	44
(n = 7)	Min–max	76–254	156–300	87–148	0–35	0–1	52–142	0–22	0–148
	SD	60	53	23	14	0.4	30	9	67
	Median	186	225	129	6	0.3	91	12	0
Group 2	Mean	113	209	128	28	18	89	18	15
(n = 8)	Min–max	54–144	174–243	105–151	0–112	0–104	43–115	0–42	0–52
	SD	29	29	18	40	36	27	17	20
	Median	122	217	132	10	1	96	12	4
Group 3	Mean	151	216	137	19	29	110	45	13
(n = 10)	Min–max	93–222	154–273	96–174	0–92	0–251	80–145	12–87	0–69
	SD	37	44	28	30	78	20	23	22
	Median	148	219	137	5	1	103	46	2
Group 4	Mean	118	236	165	33	29	116	64	44
(n = 5)	Min–max	78–176	153–353	107–247	0–92	0–61	56–164	17–158	0–103
	SD	40	73	52	37	29	39	55	52
	Median	101	216	151	24	27	119	53	15

[a] Including losses due to N emissions from volatilization in stables houses and storage (15%), during application to soil (15%) and from manure on pasture (75%).

[b] Harvested N except grassland and maize (e.g., oats, rape).

density does not necessarily lead to higher resource use efficiency or sustainability. For instance, Broom *et al* (2013) showed that livestock density of more than 4 LSU ha^{-1} in silvopastoral systems can result in high livestock production, while meeting to objectives of sustainability, biodiversity, and welfare for animals.

3.2. N input-output flows

Table 2 shows annual total N input and N outputs for farm in groups 1–4. Manure was the main N input source for all groups on average. Compared with available manure N amounts (excluding losses), mineral fertilizer was the main N source for farms in group 1 (60%) and 3 (52%). Group 2 and 4 farms used more N from manure (53 and 58 %, respectively) than from mineral fertilizer (47 and 42%, respectively). The area-related mineral fertilizer input differed greatly, ranging from a maximum of 178 ± 60 kg N ha^{-1} (group 1) to a minimum of 113 ± 29 kg N ha^{-1} (group 2). Available manure N was also a major N input source for which an increasing trend from group 1 (119 ± 23 kg N ha^{-1}) to group 4 (165 ± 52 kg N ha^{-1}) was observed. A similar trend was seen for gross manure N amounts, but the difference between the groups was smaller, ranging from 209 ± 29 kg N ha^{-1} in group 2 to 236 ± 73 kg N ha^{-1} in group 4. This is attributable to the high N losses from manure on pasture (75%), so that the gross values were reduced by just under half for groups with pasture grazing. For mineral fertilizer N ($p = .088$), manure N ($p = .570$), and available manure N ($p = .935$), no significant differences in trends were identified.

Manure imports and/or exports were observed on 19 of the 30 farms. On farms in groups 2 and 4, the amounts were similar but double the amount on farms in group 1 (13 ± 14 kg N ha^{-1}), considering the total sample size. Farms in all groups with manure imports had at least 18 kg N ha^{-1} on average, with the exception of group 1 (0.4 ± 0.4 kg N ha^{-1}). BNF was assigned to manure in the present study, but plays a small role in total N input. Based on farm-specific estimates of harvests and crop-specific parameters, only one farm in group 2 stated BNF in grain legumes. Generally, no BNF is expected on specialized dairy farms due to the high intensity of grassland management (Stein-Bachinger *et al* 2004).

Also N outputs are depicted as N flows per average farm hectare, so the N uptake per crop does not indicate yields per hectare but the share of total N flows per hectare of total UAA (ha), considering the total sample size. Farms in group 4 showed the highest N output from grassland (116 ± 39 kg N ha^{-1}) and the highest N output from maize (64 ± 55 kg N ha^{-1}) among all the groups. For maize, an increasing tendency from group 1 to group 4 was observed ($p = .012$), while no clear trend was noted for grassland or other crops. There were some similarities in the distribution of N outputs: on farms in all groups, grass from grassland was the main N output, followed by maize and other crops. An exception was observed for farms in group 1, where N yields with maize and with grass were smaller than with other crops. Due to the fact that the yields differed greatly related to total

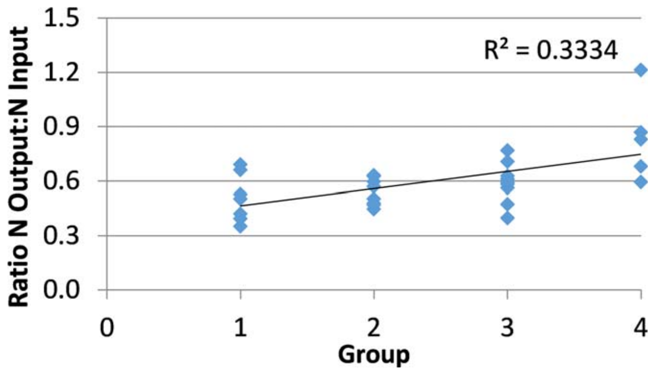

Figure 2. Ratio of all nitrogen (N) outputs (including harvest and animal products sold) to N inputs (including mineral fertilizers, gross manure, biological N fixation, atmospheric deposition) on farms in group 1 (full grazing) to group 4 (zero grazing).

UAA and that the 18 forage production farms included in the sample cultivated other crops than grassland and maize (rapeseed, oats, wheat, barley, rye, and others), different cultivation systems and crop mix were detectable.

The gross N output:input ratio on average of the groups increased slightly from full grazing to zero grazing management (figure 2): 0.51 ± 0.13 (group 1), 0.54 ± 0.07 (group 2), 0.59 ± 0.11 (group 3), and 0.84 ± 0.24 (group 4). Groups 1, 2, and 3 showed similar mean values and similar variations, while group 4 showed higher mean values, but also greater variation. A ratio >1 was only observed in group 4 (1.21). The trend of an increasing N output:input ratio from group 1 to group 4 was significant ($p = .019$).

In addition, it was observed that annual purchases of concentrates exceeded the amount of concentrates fed annually. Therefore, the concentrate stock was estimated for each farm and the concentrate intake was based on the daily feed ration following farm-specific data. An increase in concentrate feed N intake per LSU and year was observed from intensive grazing (group 1) to zero grazing (group 4). Group 4 farms showed the highest concentrate feed N intake (73 ± 16 kg N), followed by group 3 (53 ± 17 kg N), with group 1 (49 ± 6 kg N), and group 2 (47 ± 8 kg N) at a similar level. The difference between group 1 and group 4 was significant ($p = .012$). This shows that indoor systems with zero grazing seem to rely to a higher extent on concentrate feed, although they are known to be better at planning and adjusting feed rations (Powell *et al* 2010) and thus should have better conditions to utilize roughage efficiently.

'Pasture system' was considered as a separate sub-system in this study, as the exact proportion of pasture area was unknown and pasture uptake provided only an approximation. The mean over-/undersupply of N on pasture, taken as the difference between manure N on pasture and pasture uptake, was -21.7 ± 16.3 kg N ha^{-1} grassland for all farms with a pasture grazing system. This potential undersupply can be compensated for by soil N stock, diffuse N sources such as ATD, or even additional mineral fertilization not reported in NutC.

3.3. Total N balances and farm-NUE

Table 3 presents the mean, standard deviation, minimum and maximum values, and median of total gross N balances and the different types of NUE for farms in group 1 to group 4. Farms with intensive pasture management (group 1) had a total average annual surplus of 256 ± 83 kg N ha^{-1}, followed by group 2 (223 ± 28 kg N ha^{-1}), group 3 (239 ± 28 kg N ha^{-1}), and farms with zero grazing systems in group 4 (179 ± 38 kg N ha^{-1}). The range (min-max) was 162–380 kg N ha^{-1} for group 1, 182–267 kg N ha^{-1} for group 2, 137–477 kg N ha^{-1} for group 3, and 123–212 kg N ha^{-1} for group 4. The mean values showed a decreasing tendency in N surplus from the full grazing to zero grazing systems, with the exception of group 3 farms, but the differences between group 4 and each group with pasture grazing was more than 19%. Even though these differences were evident, they were statistically not significant ($p = .062$). For farm-NUE, no trend was observed. Group 3 farms showed the lowest farm-NUE (32 ± 9 %), followed by farms in group 1 (40 ± 15 %) and group 2 (43 ± 18 %). The highest farm-NUE was observed for group 4 farm (50 ± 23 %). The differences between groups were not significant ($p = .372$).

The average total gross N balance for all 30 farms at farm level was 228 kg N ha^{-1}, with an average farm-NUE of 40%. This value is similar to that in reported by Kelm *et al* (2007) for eight conventional dairy farms located in the Schleswig-Holstein region of Germany, which had an average farm-NUE of 34%. That study included full-grazing farms and zero grazing farms, and found that N balance and NUE did not differ greatly between these systems. Akert *et al* (2020) also observed an increase in (net) farm-NUE for commercial dairy farms from full-grazing to part-time grazing with substantial concentrate feed input. In contrast to the present study, the total N-balance raised as the use of concentrates increased. This may be because all farms in the present study fed considerable amounts of concentrates and farms in group 4 purchased considerably less mineral fertilizer

Table 3. Key data on total nitrogen (N) balance and different types of nitrogen use efficiency (farm-, field- and feed-NUE) on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing). Mean, standard deviation (SD), lowest value (Min), highest value (Max) and median (n = 30) for the reference year 2014.

		Balance total [kg N/ha]	Farm-NUE [%]	Field-NUE [%][a]	Feed-NUE [%]
Group 1	Mean	256	40	46	22
(n = 7)	Min–max	162–380	27–61	26–66	18–27
	SD	83	15	16	3
	Median	233	34	38	21
Group 2	Mean	223	43	40	23
(n = 8)	Min–max	182–267	20–77	33–52	20–25
	SD	28	18	7	2
	Median	223	39	39	22
Group 3	Mean	239	32	47	25
(n = 10)	Min–max	137–477	20–48	32–69	19–30
	SD	94	9	10	4
	Median	210	33	46	26
Group 4	Mean	179	50	58	27
(n = 5)	Min–max	123–212	29–89	45–74	23–34
	SD	38	23	11	4
	Median	196	46	58	27

[a] Harvested N amount according to Internal Roughage Reporting, manure N amount according to on-farm calculation based on substance flow analysis (SFA) equation (3).

(table 3) than group 1. Indoor manure collection may result in a more extensive collection and, thus, in a higher degree of manure utilization. Quemada *et al* (2020) investigated the effects of externalized N inputs on NUE of agricultural farms in EU countries. For that, N losses for production of imported concentrate were considered (NUE from 25 to 75 %) whereas farm-NUE decreased by up to 15%, depending on country and farm type. In this study, we suppose that the consideration of externalities should include both import of concentrates and exported manure amounts. For this, farm-NUE including NUE for purchased concentrates and exported manure was calculated (table A2). We found that both factors can play an important role depending on their occurrence and magnitude at farm level. If external systems reach a high N use efficiency, our results are supported even when considering externalities. Inefficient external systems flatten the results so that trends are no longer recognizable. According to the system boundaries set, modifications need to be done with regard to calculation (Powell *et al* 2010) and assessment of NUE values (EU Nitrogen Expert Panel, 2015).

The EU Nitrogen Expert Panel (2015) developed a simple 'traffic light' indicator scheme based on Brentrup and Palliere (2010) for mixed crop-livestock systems differentiated according to livestock density. According to this scheme, a farm-NUE over 60% (for 2 LSU ha^{-1}) and 80% (for 1 LSU ha^{-1}) indicates soil mining; while a value less than 20% and 30%, respectively, indicates a high risk of N losses. Based on this, 47% of farms in the present study were within the optimum range, with NUE from 30 to 60 %. Farms in group 3 were on average at the lower limit with 32 ± 9 %, close to a risk of N losses, and group 4 farms were on average at the upper limit with 50 ± 23 %, close to a risk of soil mining. However, the EU Nitrogen Expert Panel (2015) points out that the proposed target values are tentative, with fluid boundaries.

Nitrogen surpluses reported previously by Gourley *et al* (2011b) for different dairy production systems fell within a wide range, from 47 to 600 kg N ha^{-1}, while farm-NUE ranged from 14 to 50 % (n = 41). In the present study, the range was slightly more moderate for both, with N surplus varying from 123 to 477 kg N $ha^{-1}$and farm-NUE from 20 to 89 %. The lowest N balance and the highest farm-NUE were found for farms in group 4, possibly due to a better targeted feeding, high amounts of manure for application accompanied by below-average purchases of mineral fertilizers, and a positive trade balance with regard to manure (Export > Import) (Powell *et al* 2010). According to Scheringer (2002), management measures to improve NUE can be addressed on three levels: animals (feeding, performance, stock), excrement (housing, storage, application) and utilized agricultural area (fertilization, grazing, cutting, catch crops, N-efficient crops).

The total N balances indicate the environmental pressure by revealing sources of unutilized N, and thus N losses, within livestock farming systems. Environmental impacts, i.e., water quality, are not specified, but different NUE levels can be used as a proxy for potential environmental effects. For this, additional long-term data would be needed on harvesting quantities, the intensity of mechanization, and site characteristics, in particular climate and soil properties (Schulte *et al* 2006).

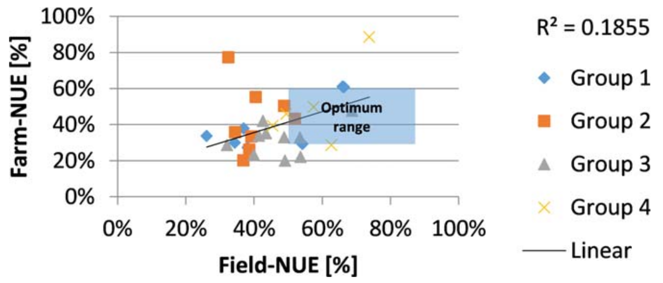

Figure 3. Relationship between field-nitrogen use efficiency (NUE) and farm-NUE of farms in group 1 (full grazing) to group 4 (zero grazing), based on data input from Internal Roughage Reporting (harvested N) and findings from substance flow analysis (SFA) (manure N).

3.4. Field-NUE

For field-NUE, the value varied from 40 ± 7 % (group 2) to 58 ± 11 % (group 4), with the other two groups showing average efficiency of 47 ± 10 % (group 3) and 46 ± 16 % (group 1). No uniform trend was seen and the differences observed were not significant ($p = .223$). It is worth mentioning that the group with zero grazing systems (group 4) had higher NUE at field level than all groups with pasture grazing. In pasture-based systems, a considerable part of manure is left on pasture and is lost to the surrounding environment to a greater extent. Therefore, in pasture systems, on average less manure is applied compared with in zero grazing systems. Thus, higher harvested N in zero grazing systems leads to more efficient N use at field level. Machmüller and Sundrum (2016) observed similar field-NUE for dairy farms in Germany, with an average of 58 ± 6 % without differentiating between pasture management systems. Differences may be due to the rather lower livestock density (1.3 ± 0.9 LSU ha^{-1}) and the associated lower amount of manure. According to the EU Nitrogen Expert Panel (2015), the optimal range is 70%–90% for field-NUE, or less strictly 50%–90%. Below 50%, there is a risk of inefficient N use and N losses, and also a risk of soil degradation and diminishing soil fertility, because nutrient uptake by crops and unavoidable N losses exceed the N amount applied to the soil (Brentrup and Palliere 2010). In the present study, only group 4 farms were in the optimal efficiency range. Group 1, 2, and 3 farms were on average below the threshold 50% level of efficiency and posed a risk of N losses. Efficiency-increasing actions should be taken if field-NUE remains at this low level over several years, including e.g., (technical) measures to increase N availability of manure in order to reduce total N inputs.

A positive relationship was found between farm-NUE and field-NUE (figure 3), i.e. as a tendency higher field-NUE are linked to higher farm-NUE. Only a few farms from each group were located in the optimum range (blue shaded area in figure 3) and thus farms from all groups need to improve their NUE, especially on field level.

For comparison, in 2014 field-NUE in Germany was around 64%, slightly above the average of the 28 EU member states (62%) and behind Romania, with the highest efficiency (90%). From 2004 to 2014, an increase in field-NUE in most EU member states has been observed (Eurostat 2018).

3.5. Feed-NUE

Feed-NUE showed a slightly increasing tendency from intensive pasture farming towards zero grazing systems, with significant differences between the groups ($p = .028$). Group 1 farms showed the lowest feed-NUE (22 ± 3 %) and group 4 farms the highest (27 ± 4 %). These findings are in line with Powell *et al* (2010) and with Arriaga *et al* (2009), who found that conventional dairy farms in Spain with mean livestock densities of 2.1 LSU ha^{-1} had feed-NUEs of 19 to 32 %. According to Chase (2003), feed-NUE values between 20 and 25 % indicate potential for improvements, values of 25 to 30 % are most common, values between 30 and 35 % are above average, and feed-NUE greater than 35% is excellent. The results of the present study indicate potential for improvement especially for farms with intensive grazing (group 1).

A positive relationship was observed between farm-NUE and feed NUE (figure 4), i.e. as a tendency higher feed-NUE are linked to higher farm-NUE. Only one farm (group 3) was near the optimum range defined by Chase (2003) and EU Nitrogen Expert Panel (2015). Farms in all groups need to improve their efficiency in terms of feed-NUE, either by decreasing inputs (feeding) or increasing outputs (performance). With regard to the distributions within and across the groups, we see potential for improvement in every group. For instance, N-reduced feed is already established on the market. There is further potential for optimization for all groups,

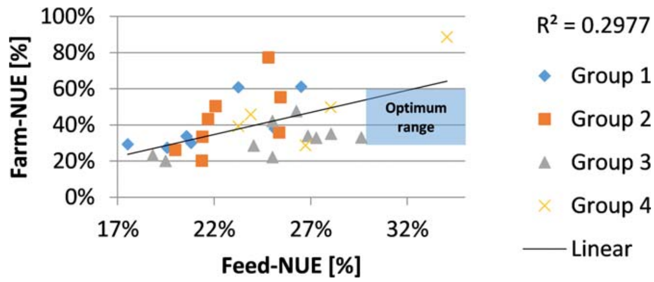

Figure 4. Relationship between feed-nitrogen use efficiency (NUE) and farm-NUE of farms in group 1 (full grazing) to group 4 (zero grazing).

particularly by means of digitization, and automated and individual feeding systems that respond to the nutritional needs.

Use of different methods in quantification of outputs makes comparability more difficult. While feed-NUE in most studies refers to milk as the only output, some approaches also include meat (Kelm *et al* 2007) and manure as a valuable product (Uwizeye *et al* 2014).

3.6. Overall NUE assessment

Farms in group 4 had the highest NUE on all levels, i.e., optimum farm-NUE and feed-NUE and field-NUE close to the optimum range. Also, the average total N balance for group 4 farms was far lower than for farms in the other groups. The ideal case of relatively high nutrient efficiencies and relatively low N surpluses was identified (Eurostat 2018), and the N outputs in harvested products were largely consistent (table 3). This supports findings in several explorative studies and farm analyses which indicate that N balance can be decreased while NUE remains constant or increases (EU Nitrogen Expert Panel, 2015). It also supports findings that farm-NUE in zero grazing systems is generally higher than in pasture-based systems, probably due to more precise and timelier information on the nutritive value of feed, so that the total feed mix can be better tuned (Daatselaar *et al* 2015, Powell *et al* 2010). For pasture-based systems, optimization of rations is hampered by varying pasture quality and differences in intake between seasons and farms (Jacobs and Rigby 1999). Therefore, we found indications supporting H1, as the N indicators investigated differed depending on the grazing system, although most differences were not statistically significant.

In this study, N balance and NUE were analyzed based on one year of data only. Multi-year data are available for purchases and sales of mineral fertilizers and manure, and for concentrate feed rations on certain farms. These data appeared to be rather unchanging, so that N balance and NUE can be considered rather constant and robust over time, which in turn leads to a more precise calculation of respective NUEs. However, 2014 was a good year for farming in Germany due to a mild winter and early onset of the growing season, resulting in German grain harvest, including grain maize, reaching a new record of just under 52 million tons (+11% on the six-year average) (BMEL 2014). Similarly, high grain yields cannot to be expected as the long-term average, so high yield levels need to be considered while interpreting the findings of this study. Moreover, if data are available, it is advised to calculate NUE and N balance over several years for better representation of the average situation.

The present study also showed the impact of data reliability and system boundaries set in analysis on field-NUE values. Farms with roughage production, particularly farms with a pasture-based management system, are more likely to be affected by data inconsistencies regarding farm-internal flows than farms cultivating cash crops. As shown in this study, quality of the data must be considered and plausibility must be checked in order to obtain robust results. Thus, we regard H2 as confirmed.

4. Conclusions

Analysis of farm N balances and NUE on different levels, based on substance flow analysis of N in different dairy farming systems in northwestern Germany, revealed indications of environmental pressure due to N losses. Potential for improvement in NUE in groups of farms with systems ranging from full grazing to zero grazing was identified, and should be pursued. Zero grazing systems show higher farm-NUE compared to grazing systems which can be attributed to more precise fertilizing and feeding management. The proportions of arable land used for grass, maize, and other cash crops did not have any marked impact on farm-NUE, but farms with a high proportion of N from cash crops showed high NUEs on farm-, field- and feed-level.

Total N balance decreased from full grazing to zero grazing, accompanied by an increase in farm-NUE and feed-NUE. On field level, higher efficiency was identified for zero grazing farms. Thus, the results can be used for benchmarking dairy farms in the study region. However, farm-NUE varied greatly between farms within groups. Thus, there is large scope for improvements without change of grazing management, or even switching to zero grazing.

Manure N and roughage N amounts are associated with high uncertainty when converting farm data into key figures, and both are frequently estimated from standard values. Here the amounts were calculated using detailed internal data, revealing discrepancies with values in farm data reporting. This finding needs to be taken into consideration in order to avoid systematic over- or underestimations of field balances and field-NUE. Therefore, farm-specific SFA can be used both to check data robustness and as a disaggregated flow analysis approach to identify N loss zones. As this is also an important finding for control authorities, plausibility checks based on SFA should be considered for further activities. If statutory NUE reporting is introduced as a complement tool to N balance, the key role of accurate N flow data should be considered by policymakers. More accurate documentation of feed imports and composition could enable the identification of N inefficiency hotspots. Otherwise, unidentified N surpluses can circulate in the system (e.g., as soil stock) or be lost as emissions (e.g., NH_3), while N inefficiencies remain constant at farm level as long as the sums of N inputs and N outputs do not change. An increase in NUE can only be achieved by increasing the overall output or by reducing the overall input. However, the impact of changed NUE on N surplus and potential environmental pollution is uncertain. Thus, both NUE for benchmarking the performance of farm nutrient management, and nutrient balances, as indicator for potential environmental pollution are recommended.

In order to assess dairy farming system sustainability according to national/international goals, further key parameters (e.g., animal welfare, biodiversity, landscape function) need to be considered, in addition to the indicators analyzed in this study. Further investigations are also required to allow comparability across all agricultural production systems. Political instruments and regulatory approaches need to find appropriate ways to reduce widespread excessive N surpluses and simultaneously increase NUE in farming systems in Germany. International comparability and benchmark setting are currently hampered by lack of uniform methodology, which should be harmonized in future work.

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