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The Effect of Diet and Farm Management on N_2O Emissions from Dairy Farms Estimated from Farm Data

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Abstract: The N_2O emissions of 21 dairy farms in Germany were evaluated to determine the feasibility of an estimation of emissions from farm data and the effects of the farm management, along with possible mitigation strategies. Emissions due to the application of different fertilisers, manure storage and grazing were calculated based on equations from the IPCC (Intergovernmental Panel of Climate Change) and German emission inventory. The dependence of the N_2O emissions on fertiliser type and quantity, cultivated crops and diet composition was assessed via correlation analysis and linear regression. The N_2O emissions ranged between 0.11 and 0.29 kg CO_{2eq} per kilogram energy-corrected milk, with on average 60% resulting from fertilisation and less than 30% from fertiliser storage and field applications. The total emissions had a high dependence on the diet composition; in particular, on the grass/maize ratio and the protein content of the animal diet, as well as from the manure management. A linear model for the prediction of the N_2O emissions based on the diet composition and the fertilisation reached a predictive power of $R^2 = 0.89$. As a possible mitigation strategy, the substitution of slurry for solid manure would reduce N_2O emissions by 40%. Feeding cows maize-based diets instead of grass-based diets could reduce them by 14%.

Keywords: GHG emissions; dairy cow; nutrition; nitrogen fertilization; feed cropping; pasture

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1. Introduction

The agricultural sector (crops and livestock) is a substantial contributor to greenhouse gas (GHG) emissions; globally, it represents approximately 14% of the anthropogenic GHG emissions [1]. Livestock production systems contribute about 42% of total GHG production from agriculture, 28% of which is associated with direct emissions of enteric fermentation (CH_4) and 14% (CH_4 and N_2O) related to manure handling, storage and its use as fertilizer [2]. In 2018, the German agricultural sector ranked second (after France) in total GHG emissions among the 28 EU countries; it produced about 63600 Gg CO_{2eq}, which corresponds to 7.4% of the greenhouse gas emissions in Germany. German agriculture emissions have decreased significantly since 1990, mainly due to reduced livestock numbers, more efficient fertilizer application, and improved manure management. In 2017, the emissions of N_2O were lower than those in 1990 by about 16.8% and the CH_4 emissions by about 26.8% [3]. Nonetheless, these efforts have to be intensified to reach the German self-imposed goal to reduce GHG emissions by 55% by 2030.

As a major GHG, N_2O is the most powerful ozone-depleting compound emitted by human activity [4]. In agricultural land-use systems, organic and inorganic nitrogen fertilizers are the overall main contributors to anthropogenic N_2O emissions [5]. Many factors, like the animal diet and its protein content, the type of storage and the farming system, influence the production of N_2O from manure. In order to determine which variables are the principal players affecting N_2O emissions on milk producing commercial farms, several studies have been conducted and employed different systems of analysis [6–9]. Unfortunately, most

published studies focus on just a part of the N_2O emission sources in the dairy farm and rarely consider the entire dairy farm system. The effect of animal diet is often not included in the calculation and just the quantity of the manure is considered. This gives an incomplete view of the entire N_2O emissions scenario on the farm, as the animal diet composition is a major deciding factor for GHG emissions from manure [10].

Furthermore, most of these studies were performed using data from the literature or models under standard conditions. However, such data are often gathered from very old research to amass a large database or selected with severe restrictions to achieve database homogeneity. These procedures can seriously affect the study results and do not reflect the typical variability of farm systems [11–13]. Very few studies have analysed all the N_2O sources in the dairy farms and explored the connection between variable modification inside the system and its effect on N_2O emissions [11], and even fewer have determined the emissions on the base of data coming from real farms. The complexity of collecting valid farm data and successively controlling and normalizing all farmer-retrieved information has resulted in few direct farm-based interview studies [9,14].

Against this background, we decided to investigate the power and the limits of an assessment of N_2O emissions based on farm data. In particular, we aimed to reconstruct N_2O emissions produced from the whole farm (milking cows, heifers and calves) during the entire milk production process (from the feedstuff production to the manure management) and consider also the animal diet, using all the information which is usually available and well-documented in a dairy farm. For this aim, we selected farms from three regions in Germany, different in terms of animal breed, farm dimensions, animal diets, manure management and the presence of pasture, and collected all the necessary data for the N_2O emissions estimate. In the present study we analysed the data in order to address the following research questions:

1. How accurately can emissions be predicted from farm data?
2. Which parameters make the highest contribution to an N_2O emissions estimate?
3. What mitigation strategies can be reasonably deduced from farm data?

2. Materials and Methods

2.1. Data Collection

The farm data were collected over a period of 24 months from 21 dairy farms located in three German regions (north, central and south; see Figure 1), which can be considered to represent the dairy farm variability in these regions in terms of animal breed, farm dimensions, feed production and quality, fertilisation, manure management and climate. The data were collected in situ from the farms' documentation and through personal interviews with the farmers, as reported in detail in Figure 2, in order to obtain all relevant information to estimate the total N_2O emissions of the farms.

Information was collected on the following aspects of farm management: milking cow number and reproductive cycle, milking cow diets, feedstuff quantity and quality, grazing management, crop production and fertilisation, purchased inputs (off-farm feedstuffs and chemical fertilisers), manure management, milk production and quality, total farm surface (TFS; including both the surface used for the animal feedstuff production and the surface used for the production of crops for other purposes) and in-farm and off-farm feedstuff surface (FS; calculated as the sum of the total surface necessary for the production of all in-farm and off-farm feedstuffs used to feed the milking cows, the heifers and the calves in the farm). Monthly milk analyses and productions were collected from the farms delivering the milk. Weather condition data were obtained from the Deutscher Wetterdienst (www.dwd.de, accessed on 17 November 2020) archive. The N_2O emissions from crop residues were not included in the calculation because of their minimal contribution to the total farm emissions [15]. Also, the indirect N_2O emissions were not considered, they were not connected directly with the farms under study. In the following sections, we describe in detail how the farm data were collected, controlled and, when necessary, corrected.

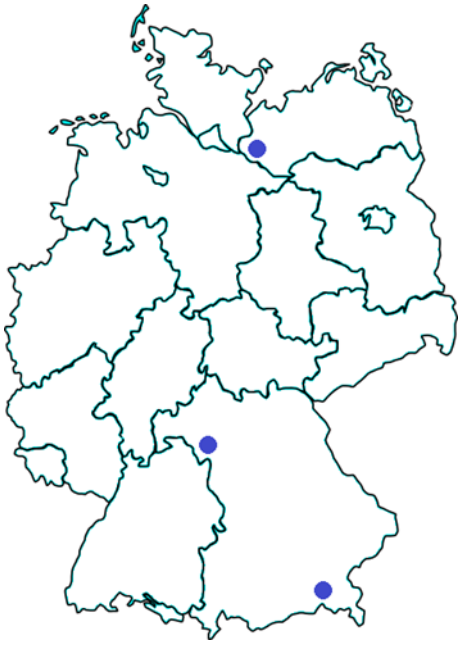


Figure 1. Location of the production sites under investigation: north (farms N1–N5), central (farms C1–C4) and south (farms S1–S12); adapted from http://www.clker.com/clipart-germany-4.html# (accessed on 2 July 2021).

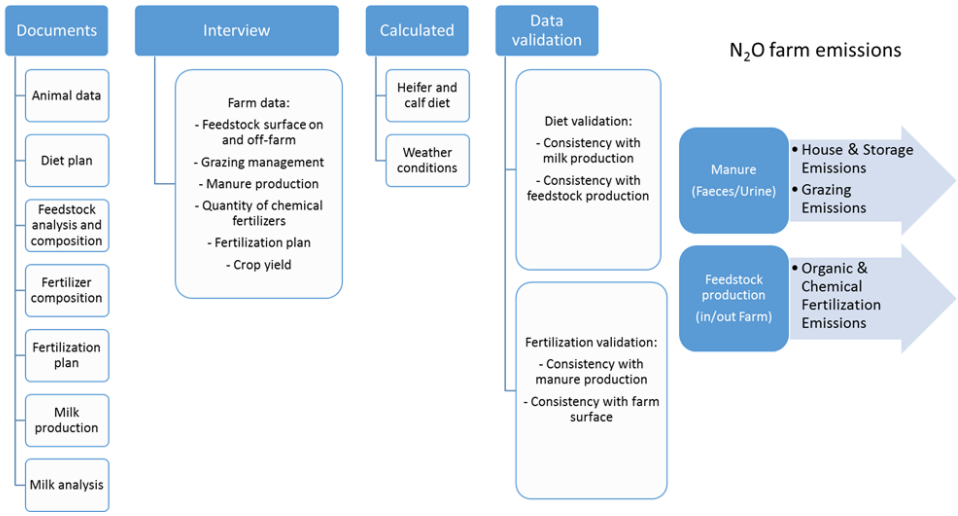


Figure 2. Scheme of the collection, calculation and control of the data from the 21 selected dairy farms analysed in the present study.

2.2. Diet for Milking Cows

The milking cow diets during the lactating period and the dry period were determined on the basis of the diet plans of the farms, which record the feedstuff used in the diet, the quantity and the period. For all feedstuffs produced on the farm, chemical and nutritional analyses were available; for the commercial feedstuffs, the chemical composition was provided. Using this very detailed information, the diets were verified for each farm against the net energy lactation (NEL) and the digestible protein (nXP) values corresponding to reported milk yields and then consequently adjusted to account for actual feedstuff usage.

For the nutritional composition of the fresh grass during the grazing period, values from the literature were used [16,17]. For statistical analysis purposes, feedstuffs were classified as grass, leguminous grass, maize or other cereals.

2.3. Diets for Heifers and Calves

The younger animals were grouped as follows: calves up to 6 months of age, heifers up to 2 months prior to the first calving and heifers from 2 months prior to the first calving to the calving. No detailed heifer and calf diets were recorded on the farms, but the information about the farm organisation was sufficient to recreate and estimate the diets for these groups of animals on the dairy farms. The heifer diet was elaborated for each farm based on all the information obtained from and the feedstuff used on that specific farm. To estimate the final heifer body mass for each farm, we included both the milk production of the entire breeding herd (between 6000 and 10,000 kg milk produced per animal per year) and the age of the first calving. The data were then cross-referenced with heifer body mass gain per month, as reported by Hoffmann and Funk [18], to determine the intake of dry matter (DM), crude protein (XP) (both in kg an^{-1} y^{-1}) and metabolizable energy (ME, in MJ an^{-1} y^{-1}) needs for each heifer group according to the nutritional values reported by Weiß et al. [19] and Kirchgeßner et al. [20]. A different approach was employed for heifer diets during the final two months before first calving in order to maintain a direct link with actual farm situations [20]. Specifically, for this group of heifers the dry cow diet was used, except when farmers reported differently, such as when animals received a diet identical to the milking cows.

2.4. Crop Yields and Fertilisation

Cultivated feedstuff surface (expressed in ha) and yield data (expressed in t DM ha^{-1} y^{-1}) collected during the interviews were verified for consistency with region-specific yield ranges [21,22]. Similarly, verifications were completed for climate conditions, including average losses during harvest and storage, which were reported as 10% for grains [23,24], 15% for maize silage [25,26] and 20% and 25%, respectively, for grass silage and hay [27]. Surfaces were delineated as total farm surface, which included the feed surface (with the accompanying surface to produce off-farm concentrate and feedstuff), feed surface per livestock unit (LSU, referred to 500 kg body mass and calculated for milking cows + heifers + calves) and feed surface per kg energy-corrected milk (ECM).

Nitrogen fertilisation (organic and chemical) necessary for cow feed cultivation, both on- and off-farm, was verified for regional agricultural practice variation, as well as crop N needs [21,22]. Corrections were made as necessary for out-of-range cases (such as fertiliser amounts below crop needs or over-fertilisation by more than 20%) [28]. In these cases, the nitrogen fertilisation was increased or reduced to the adequate quantity. Finally, organic fertilisation type (liquid as slurry or solid as manure) and amount were also checked against farm livestock units. Fertilisers were grouped according to the official IPCC guidelines [1] as: liquid organic (slurry), solid organic (manure), NP fertilisers, urea (46% N), calcium ammonium nitrate (CAN, 27% N) and NPK fertilisers (27% N).

2.5. N_2O Emission Calculations

2.5.1. Excreta Calculations

The N_2O emissions produced by chemical and organic fertilisation of the on-farm feedstuff crops and of the off-farm feedstuffs and concentrates were estimated for each farm as described by Haenel et al. [3]. Total emissions require inclusion of more than those applied for fertilisers; they include those released during grazing, animal housing and manure storage. For this reason, we first estimated the nitrogen excreted by the cows as the N balance in the living animal according to the following equation:

$$N_{excreted} = N_{feed} - N_{milk} - N_{body\ mass\ gain} - N_{calf}, \quad (1)$$

where N_{feed} is the nitrogen amount in the diet, N_{milk} is the nitrogen amount in the produced milk, $N_{body\ mass\ gain}$ is the nitrogen amount in cow body mass gain and N_{calf} is the nitrogen amount in calf body mass. Table 1 lists the values used for these calculations.

The milking cow body mass was collected during the interviews in the dairy farms. The body mass gain of the heifers was estimated according to Hoffman [29] for the breed Holstein and according to Andrýsek et al. [30] for the breed Fleckvieh. The body mass gain curves were adapted to the final heifer body mass, which was collected during the farm visits and double-checked with the age of the first calving and the milk production of the herd.

Table 1. Biometric data used for N balance.

	Details	Value	Reference
Calf body mass	Holstein	40 kg	[18]
	Fleckvieh	45 kg	[31]
N content	Calf	0.029 kg N kg^{-1} BM	[32]
	Animal body mass gain	0.024 kg N kg^{-1} BM	[32]
	Milk protein	0.638 kg N kg^{-1} ECM	[32]

BM = body mass; ECM = energy-corrected milk.

We calculated the fraction of N excreted in faeces using two procedures, one for milking cows and one for young cows (heifers and calves). In the case of the former, we used Equation (2), provided by Haenel et al. [3]:

$$m_{\text{faeces}} = a \cdot m_{\text{feed}} + x_{\text{N}} \cdot \left[b \cdot DM + c \cdot DM^2 \right], \quad (2)$$

where m_{faeces} is the N excreted in faeces (kg N an^{-1} y^{-1}), m_{feed} is the N intake with feed (kg N an^{-1} y^{-1}), x_{N} = 0.16 kg N kg^{-1} is the average N content in feedstuff crude protein and a = 40 g kg^{-1}, b = 20 g kg^{-1} and c = 1.8 g kg^{-2} an d are empirical constants. For heifers and calves, m_{faeces} was calculated according to Equation (3), as presented by Dämmgen and Hutchings [33] and generally used for cattle:

$$m_{\text{faeces}} = (1 - X_{\text{DE}}) \cdot m_{\text{feed}}, \quad (3)$$

where X_{DE} is the ratio between the digestible energy (DE) and gross energy (GE) of the feedstuff. To complete the excreta calculation, nitrogen excreted in the urine was calculated as the difference between total N excreted (from Equation (1)) and N excreted in faeces (from Equation (2)).

2.5.2. Emission Factors

Emissions were then estimated using the same emission factors (*EF*s) as in the German emission inventory [3] (Table 2). We considered four main emission sources: (1) N in the chemical fertiliser (N_{chem}), (2) N in the organic fertiliser (N_{org}), (3) N in manure excreted in the animal house (N_{store}) and (4) N released directly during grazing on the pasture (N_{graz}).

Table 2. Emission factors (EFs) used for calculations [3].

	Details	EF_{N2O} (kg N_2O-N kg^{-1} N)	EF_{NO} (kg NO-N kg^{-1} N)	EF_{NH3} (kg NH_3 kg^{-1} TAN)
Chemical fertiliser	NP	0.0125	0.012	0.0107 + 0.0006·T
	NPK and CAN	0.0125	0.012	0.0080 + 0.0001·T
	urea	0.0125	0.012	0.1067 + 0.0035·T
Organic fertiliser	slurry, natural crust	0.0125	=0.1·EF_{N2O}	0.15/0.54
	solid manure	0.0125	=0.1·EF_{N2O}	0.45/0.90
Housing + storage	slurry, natural crust	0.005	=0.1·EF_{N2O}	0.197 + 0.045
	solid manure	0.013	=0.1·EF_{N2O}	0.066 + 0.600
Grazing		0.02	0.007	0.10

TAN = total ammoniacal nitrogen; T = mean air temperature in spring, in °C.

2.5.3. Crop Fertilisation Emission Calculations

To estimate N_2O emissions produced from crop fertilisation, it is necessary to subtract the other nitrogen-rich gaseous emissions from the total nitrogen pool, namely nitrogen monoxide (NO) and ammonia (NH_3) [3]. The emission factors are dependent on the climate and on the distribution system used; the yearly mean temperatures for each location were considered as well as the fertiliser distribution systems employed in the farms. Ultimately, the conversion of the N source to N_2O emissions is the total N minus the N fraction lost as ammonia and NO emissions. We relied on the following formulae for our determination:

- Application of chemical fertiliser:

$$(N_2O\text{-}N)_{chem} = N_{chem} \cdot \left(1 - EF_{NH_3}^{chem} - EF_{NO}^{chem}\right) \cdot EF_{N_2O}^{chem}; \quad (4)$$

- Application of organic fertiliser:

$$(N_2O\text{-}N)_{org} = N_{org} \cdot \left(1 - x_{TAN} \cdot EF_{NH_3}^{org} - EF_{NO}^{org}\right) \cdot EF_{N_2O}^{org}, \quad (5)$$

where x_{TAN} is the fraction of total ammoniacal nitrogen within N_{org}.

Indirect N_2O emissions, such as those from N fixation and deposition, were not included in the calculations because they are negligible and not significantly different among farms. The grassland renewal was not included as a source of N_2O in the calculations because in all the analysed farms, wherever grassland was present, it was permanent grassland.

2.5.4. Housing-, Storage- and Grazing-Related Emissions Calculations

To estimate the N_2O emissions produced from housing the animals and storing the manure prior to crop application, as well as N_2O emissions released during pasture grazing, we employed the following equations:

- Housing and storage prior to application:

$$(N_2O\text{-}N)_{store} = N_{store} \cdot EF_{N_2O}^{store}; \quad (6)$$

- Release during grazing:

$$(N_2O\text{-}N)_{graz} = N_{graz} \cdot EF_{N_2O}^{graz} \quad (7)$$

2.5.5. Farm Input Emission Calculations

The N_2O emissions connected to the cultivation of the purchased feedstuff of the animal diets were also included in the calculations. For the purchased feedstuff, standard fertilisations were used for the calculations of N_2O emissions, as reported in [21]. Furthermore, for each purchased feedstuff, an economic allocation value (LCA Archive) was also determined, as reported in Table 3, and introduced into the calculations in order to consider the contributions of each purchased feedstuff to the N_2O emissions of the farm.

Table 3. Allocation factors used for emission calculations.

Purchased Feedstuff	Economic Allocation Value	Reference
Pressed sugar beet silage	23.0%	[34]
Soybean meal	59.0%	[35]
Rapeseed meal	26.0%	[36]
Rapeseed oil	74.0%	[36]
Molasses pulp	5.0%	[36]
Brewers' spent grains	11.0%	[37]
Wheat straw	7.5%	[36]
Sunflower expeller	23.0%	[38]

Table 3. *Cont.*

Purchased Feedstuff	Economic Allocation Value	Reference
Wheat bran	3.8%	[34]
Linseed meal	42.5%	[34]
Malt culms	3.5%	[39]
Maize gluten meal	6.9%	[34]
Palm expeller	1.0%	[40]
Wheat meal	93.6%	[34]
Pressed potato pulp	1.0%	[41]

2.5.6. Emission Categories and CO_2 Equivalents

Emissions were calculated for the following animal categories: lactating cows, non-lactating (dry) cows, heifers 2 months before calving, heifers up to 2 months before calving and calves up to 6 months old. For four of the five farms in the northern region, the lactating cows were divided into three sub-groups according to feeding: high milk production cows, low milk production cows and primiparous cows. Estimated N_2O emissions were turned into CO_2 equivalents with a conversion factor of 298 kg CO_{2eq} kg^{-1} N_2O [1] and scaled using as a functional unit of 1 kg ECM (energy-corrected milk, with 4% fat and 3.3% protein).

2.6. Statistical Anaylsis

Farm data related to breeding conditions, cow diets and cow feed cultivation were log-normalised when they were not of normal distribution. Regional mean values were compared by means of a one-way ANOVA analysis followed by a Tukey's HSD test ($\alpha = 0.05$).

Estimated N_2O emissions were also compared within the three regions and further tested for dependence on pasture (with or without pasture) and cow breed (Holstein Frisian vs. Bavarian Fleckvieh) via a *t*-test ($\alpha = 0.05$). In addition, the dependence of the estimated N_2O emissions on the farm management conditions (diet composition, feed nutrient contents, crop yield, applied fertiliser type) was tested via a multiple linear model:

$$y \sim \beta_0 + \sum_i \beta_i \cdot x_i, \quad (8)$$

where $y = (N_2O)_{tot}$ (kg CO_{2eq} kg^{-1} ECM) and the possible predictors x_i included the diet protein content, the maize and grass amount in the diet and the maize and grass yield, as well as nominal variables describing manure quality (solid vs. liquid) and grazing habits (yes/no). Several models with different choices of predictors were fitted via ordinary least squares regression and the results were compared concerning the significance of the fitting parameters and the AIC coefficient. All the analyses were performed using the statistical program JMP version 14 (SAS Institute Inc., Cary, NC, USA).

3. Results and Discussion

3.1. Description of the Farms

The characteristics of the analysed farms are described in Tables 4 and 5. The farms contained two different breeds that related to their region: Holstein Friesian in the north, Bavarian Fleckvieh in the other two regions. Farm size (animal numbers) was highly variable among the farms; the largest farms were situated in the northern region, while the central region was characterized by smaller farms with an average of around 30 milking cows. In the southern region, most of the farm had between 40 and 60 milking cows, with the exception of a very small farm (S8, with 16 milking cows) and a larger one (S4, with 102 milking cows).

Despite the large differences in farm herd size, some key parameters of the reproductive cycle management of the animals were quite similar across all analysed farms, such as the age of first calving (mean value 28.6 ± 0.8 months) and the dry period (50 ± 7 days). Animal lifespan (5.4 ± 0.9 years) also showed no significant differences among farms; only

in the smallest farms in both the southern (S8) and northern regions (N3) did cows grow older (>7 years), but that did not lead to any strong overall correlation between cow lifespan and farm size. On the contrary, the productive cycle length was quite different among both farms and regions and was slightly (R^2 = 0.35) correlated to the farm dimension.

Table 4. Analysed farm descriptions: breeding systems.

Region	No. of Farms	Breed	Milking Cow	First Calving Age	Dry Period	Productive Cycle	Milk Production
			No.	Months	Days	Days	kg ECM an^{-1} y^{-1}
South	12	Fleckvieh					
Average			54 ^{b}	29.3	50.2	377 ^{b}	7555
Min			16	26.4	38.2	361	5900
Max			103	33.2	62.4	388	8805
St Dev			21	1.9	8.4	8	934
Central	4	Fleckvieh					
Average			28 ^{b}	28.1	49.6	373 ^{b}	7463
Min			22	28.0	41.0	367	6068
Max			38	28.3	55.7	379	8751
St Dev			6	0.1	6.0	4	1118
North	5	Holstein					
Average			266 ^{a}	27.4	47.9	430 ^{a}	7972
Min			67	27.0	35.4	405	7256
Max			486	28.2	60.2	465	8915
St Dev			155	0.5	8.0	23	572

Means with different letters within columns are significantly different (α = 0.05).

Table 5. Analysed farm descriptions: milking cow diets.

Region	No. of Farms	DM Intake	XP Intake	NEL Content	Grass	Maize	Hay	Straw	Pasture	Concentrate
		kg DM an^{-1} d^{-1}	kg XP an^{-1} d^{-1}	MJ kg^{-1} DM^{-1}	% DM	% DM	% DM	% DM	% DM	% DM
South	12									
Average		18.3	2.89	6.6	40.8 ^{a}	21.4 ^{b}	5.4 ^{a}	1.1 ^{b}	8.4	20.6
Min		16.8	2.52	6.1	31.5	0.0	0.8	0.0	0.0	4.1
Max		20.4	3.38	7.1	51.7	36.0	14.2	3.1	30.0	29.7
St Dev		1.1	0.24	0.3	6.1	10.4	3.5	1.1	12.0	7.1
Central	4									
Average		18.0	2.62	6.6	19.0 ^{b}	42.8 ^{a}	7.9 ^{a}	4.2 ^{a}	–	25.9
Min		15.3	2.17	6.3	10.6	31.9	3.0	0.4	–	18.2
Max		20.3	3.12	6.8	28.5	51.2	11.4	7.0	–	38.8
St Dev		1.9	0.34	0.2	6.4	6.9	3.1	2.6	–	8.3
North	5									
Average		18.5	2.90	6.5	36.6 ^{a}	23.8 ^{ab}	0.9 ^{b}	1.9 ^{ab}	7.2	29.3
Min		17.1	2.48	6.1	22.5	0.0	0.0	0.4	0.0	22.6
Max		20.4	3.27	6.8	43.5	40.5	2.7	3.8	30.4	38.5
St Dev		1.1	0.34	0.3	7.5	13.9	1.1	1.2	11.8	6.2

Means with different letters within columns are significantly different (α = 0.05). DM = dry matter; XP = crude protein; NEL = net energy of lactation; ECM = energy-corrected milk.

Although the milking cow diet highly differed between the regions and within the regions, neither the dry matter intake (mean 18.3 ± 1.3 kg DM d^{-1}) of the animals nor the dietary protein intake (mean 2.8 ± 0.3 kg XP an^{-1} d^{-1}) nor the energy content (mean 6.6 ± 0.2 MJ NEL kg^{-1} DM^{-1}) showed any significant difference. These dry matter intake (DMI) values are adequate for the animal body mass and the milk production [42].

A detailed analysis of the feedstuff comprising the diets was performed and made some variations clearly visible. Grass was the main feedstuff of the diets for the milking cows in the southern region, representing more than 40% of the diet, with a maximum of about 50% in one farm (S1); the typical source of the grass silage were permanent grasslands

mainly characterised by gramineae. At four southern region farms, milking cows remained on the pasture most of the year (part of the spring, the entire summer and autumn), so that the fresh grass consumed during grazing represented about 25% of DMI on average. Small amounts of hay (5.4% of total DMI on average) and straw (1.1% of total DMI on average) were also present in the diet, of which the hay contribution varied most (0.8 to 14.2%). On average, maize represented nearly 21.4% of DMI.

The farm diet in the northern region was quite similar to that of the southern region; the only exception was the significantly lower hay content (less than 1%). Pastures were used for milking cows only in one farm, where they represented 30.4% of the dietary DM; the other northern farms had grazing available for heifers only.

In the central region, the milking cow diet differed from the other two regions, mainly because of the very low amount of grass as feedstuff in the diets and the complete absence of pasture. The grass also differed in quality, being mainly leguminosae (alfalfa) with a high N content. The main feedstuff in the animal diet was maize (42.8% on average).

Despite the high variation in dietary composition across the farms, the milk yield per animal and year did not differ. We attribute this to the homogeneity of the dietary intakes of protein, energy and DM among the farms, which are the major factors determining milk production [19].

Detailed information about the milking cow diet and the milk production is extremely important in order to elaborate the N_2O estimation. In our study the two parameters DMI and milk production were well-correlated (R^2 = 0.64). In order to also include the grazing in the diet, which for some farms can represent a large portion of the diet, the data collected on the farms had to be further supplemented with data from literature and cross-checked with the crop production and the milking cow diet. At the same time, the information about the heifers and the calves was also very sparse and had also to be reconstructed from literature data. The same difficulty has occurred in other similar studies, where information about grazing and younger animals had to be estimated in the same way [6,9,43].

The (absolute) feed surface was very variable among the farms but correlated well with the size of the herd (Table 6) and was correspondingly much larger in the northern region; on the other hand, the unitary surface, both per livestock unit (LSU) and per kg ECM, was very homogeneous among the farms, respectively 0.76 $\pm$ 0.1 ha LSU^{-1} and 1.68 $\pm$ 0.32 m^2 kg^{-1} ECM.

The in-farm feedstuff surface corresponded to the total farm surface only in very few farms that had almost complete internal feedstuff production and very low concentrate use. On all other farms, only a portion of the farm surface was used for internal feedstuff production, and the remainder was cultivated with cereals for sale, either to the food industry, to other farms or to biogas plants (particularly in the north).

Permanent grassland amounted to more than 50% in the south and only 4.7% in the central region; in the central region, the surface was cultivated primarily with leguminosae (11.6%) and maize (19.6%). Pasture surface, reserved mainly for heifers, was present on half of the farms and only in the southern and northern regions. On three farms (S6, S7 and S8), some of the permanent grassland consisted of alpine pastures which were used for grazing and were not fertilised.

The crop yields did not demonstrate any region-specific differences, except for the grassland yield being higher in the south, since the weather conditions lengthen the harvest period and thus the number of cuttings is increased (between four and six cuttings per year in south Germany, no more than three in north Germany).

Table 6. Analysed farm data: surfaces and crop yields.

Region	Total Farm Surface (TFS)	In-Farm and Off-Farm Feedstuff Surface (FS) *			Surface				Yield			
					Cer	Mai	Leg	Per. Gras **	Cer	Mai	Leg	Per. Gras **
	ha	ha	ha LSU^{-1} #	m^2 kg^{-1} ECM	% on FS	% on FS	% on FS	% on FS	t DM ha^{-1}	t DM ha^{-1}	t DM ha^{-1}	t DM ha^{-1}
South												
Average	42.5 ^{b}	59.4 ^{b}	0.7 ^{b}	1.6	1.7	11.9 ^{b}	2.3	55.4 ^{a}	6.4	17.9	10.0	9.8 ^{a}
Min	28.0	23.3	0.5	1.1	0.0	0.0	0.0	41.6	5.5	12.3	10.0	5.4
Max	60.0	102	1.1	2.7	6.2	20.3	27.5	86.0	8.0	22.8	10.0	13.5
St Dev	11.3	20.0	0.2	0.5	2.5	5.5	7.6	10.6	1.0	3.1	0.0	2.0
Central												
Average	50.0 ^{b}	36.9 ^{b}	0.8 ^{ab}	1.7	5.6	21.0 ^{a}	11.5	5.7 ^{b}	7.0	18.4	11.0	7.8 ^{ab}
Min	31.0	25.3	0.7	1.3	0.0	16.9	7.5	0.0	6.2	17.2	10.5	6.5
Max	70.0	57.9	0.8	1.9	8.2	25.9	15.4	15.4	7.8	20.2	11.4	9.0
St Dev	18.5	12.4	0.1	0.3	3.3	3.7	3.0	6.4	0.7	1.2	0.3	1.3
North												
Average	724 ^{a}	418 ^{a}	1.0 ^{a}	1.9	3.4	12.0 ^{b}	3.5	43.7 ^{a}	4.8	15.7	4.80	7.0 ^{b}
Min	128	121	0.7	1.6	0.0	0.0	0.0	23.2	3.5	11.8	4.80	5.1
Max	1994	863	1.3	2.2	9.8	21.5	17.4	57.8	6.0	22.5	4.80	9.1
St Dev	694	286	0.2	0.2	4.1	7.9	7.0	11.3	1.0	4.3	0.0	1.4

Means with different letters within columns are significantly different ($\alpha = 0.05$). * Feed surface (FS) includes not only the on-farm area used for the cows (including calves and heifers) but also the off-farm feedstuff and concentrates surface. ** Permanent grassland also includes pasture. # Cows, including calves and heifers. LSU = livestock unit; ECM = energy-corrected milk; Cer = cereals; Mai = maize; Leg = leguminosae; Per. Gras = permanent grassland.

3.2. Nitrogen Fertilization

Nitrogen fertilisation is one of the largest sources of N_2O emissions in a breeding farm. The ratio of organic to chemical fertilisers used on a farm is fundamental for a robust emissions calculation because of their differing emission factors (EFs). The chemical fertiliser type and the timing of its application affect its EF value and, consequently, its atmospheric N_2O emissions [3].

The type of N fertilisation employed, treatment period, and dosage was assessed in detail for each farm. Figure 3 indicates the distribution of fertilisers used in each farm, expressed as kg N ha^{-1}. In general, large differences in N fertilisation were not detected among the farms for the main cultivated crops (Table 7), except in the southern region, where the N amount for crop fertilisation for the permanent grassland (including the grazing surface) was significantly higher compared to the other two regions; this was particularly true for the N obtained from slurry organic fertilisation. As already explained, in the south the grass yield is higher than in the other German regions because of the weather, which means that more cuts can be made during the year. In the farms in the northern and central regions, the low N fertilisation is correlated respectively to the lower crop and grassland yields (with a few exceptions) and the large alfalfa cultivation.

Generally, about 75% of the total N distributed on fields was organic and provided by fertilisation or grazing. The organic N source was usually slurry, except for farms S8 and N2, where solid manure was employed. Solid manure has a higher emissions factor compared to slurry and its use as organic fertiliser can affect the total emissions coming from the field fertilisation [44]. Only two farms (S8 and N3) used organic fertiliser exclusively, which resulted in very low N quantities; these farms were the most extensive, as evidenced by feed-specific surfaces of 3.7 and 1.7 m^2 kg^{-1} ECM, respectively. The most common N fertiliser was CAN, which is not surprising given its low price, ease of distribution and high N content; some farms also used NP fertiliser and a few used urea, but in low doses in order to limit the risk of its alkalinity burning crop tissues.

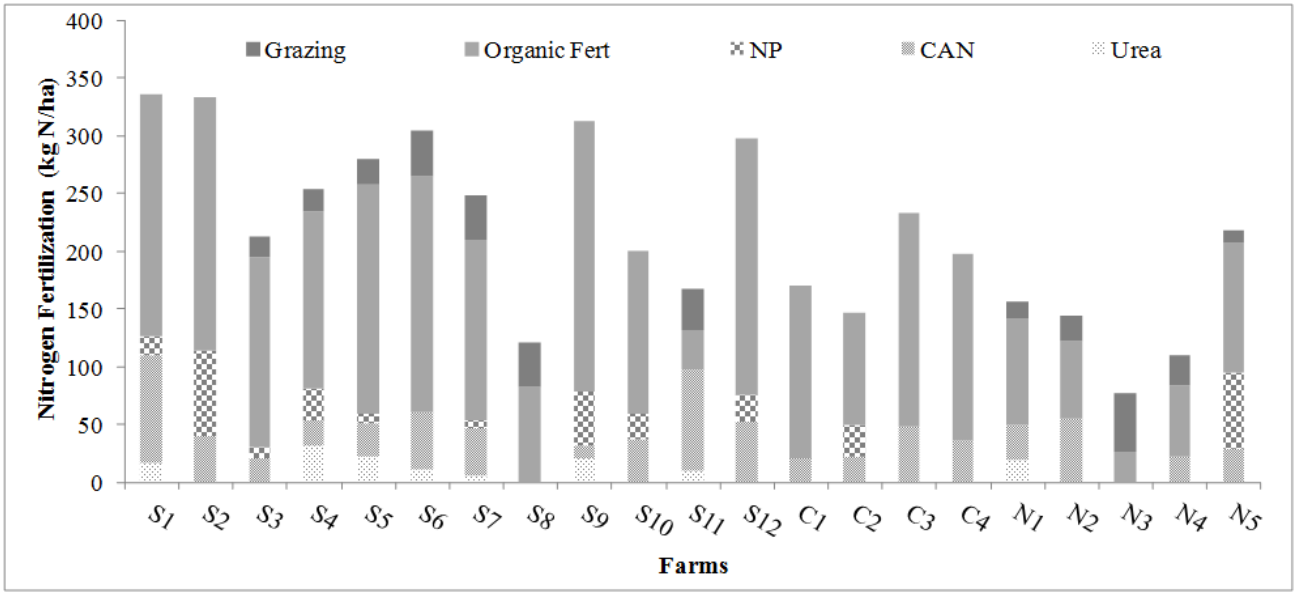


Figure 3. Amounts of organic and chemical fertilisers used on the 21 analysed dairy farms. The chemical fertilisers were nitrogen phosphorus (NP), calcium ammonium nitrate (CAN), and urea.

Table 7. Analysed farm data: nitrogen fertilisation.

Region	Chemical Fertilisation				Organic Fertilisation				Total Fertilisation			
	Cer	Mai	Leg	Per. Gras	Cer	Mai	Leg	Per. Gras	Cer	Mai	Leg	Per. Gras
	kg N ha^{-1}				kg N ha^{-1}				kg N ha^{-1}			
South												
Average	41.3	164 [a]	–	55.4	91.4	127	–	209 [a]	133	291	–	264 [a]
Min	27.0	73.7	–	0.0	45.0	0.0	–	120	101	200	–	120
Max	55.7	232	–	124	176	228	–	270	209	371	–	379
St Dev	11.9	44.2	–	36.3	50.9	55.7	–	44.5	44.1	55.4	–	66.6
Central												
Average	28.8	64.8 [b]	–	–	110	228	20.7	119 [b]	138	293	20.7	119 [b]
Min	0.0	27.0	–	–	73.5	204	19.4	57.4	122	253	19.4	57.4
Max	48.6	81.0	–	–	155	249	21.9	180	155	330	21.9	180
St Dev	20.8	22.3	–	–	33.6	16.2	0.9	61.5	13.2	28.2	0.9	61.5
North												
Average	34.2	60.3 [b]	–	38.3	71.5	192	9.5	94.2 [b]	106	252	9.5	133 [b]
Min	0.0	14.0	–	0.0	67.9	89.7	9.5	79.5	71.8	183	9.5	79.5
Max	75.6	93.2	–	133	75.0	354	9.5	108	144	368	9.5	238
St Dev	31.3	30.2	–	49.6	2.9	99.5	–	12.1	29.4	74.2	0.0	55.4

Means with different letters within columns are significantly different (α = 0.05). Cer = cereals; Mai = maize; Leg = leguminosae; Per. Gras = permanent grassland.

Maize and grass are the basic components of cow diets and could be expected to have a strong effect on farm N fertilisation amounts; surprisingly, only grass yield was correlated to mean total N fertilisation per hectare, but not maize yield (Figure 4). This was probably due to the lower N fertilisation of maize in comparison to grass N fertilisation and also because of the few farms with maize-based diets, just 4 out of 21 farms.

The largest areas of the considered farms were covered by permanent grassland, which also utilised the largest N fertilisation amounts in this study. Coherently with that, it so happens that detailed and precise information on grassland N fertilisation can provide

a rough and ready estimate of the total N needed to produce the feedstuff for the full complement of milking cows.

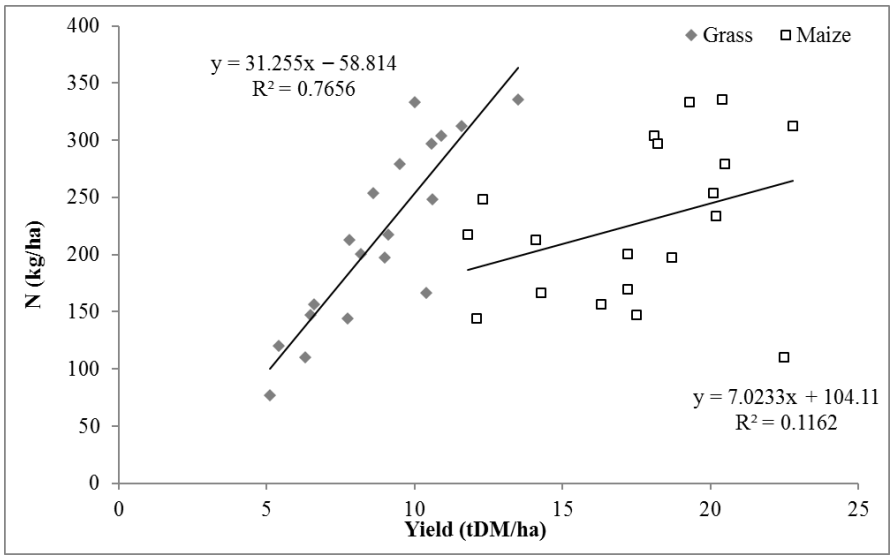


Figure 4. Linear regression between grass or maize yield and total amount of nitrogen distributed per hectare (mean values for all crops) on the farms.

3.3. N_2O Soil Emissions from Individual Feedstuffs Versus Standard Fertilisation

The soil N_2O emissions for all main diet feedstuffs were estimated for each single farm [28]. The estimated values (Table 8) were very close to standard fertilisation values presented by the KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.) [21], with some slightly higher values that we ascribed to the N over-fertilisation described in our study. Grass silage was sub-grouped into gramineae-based grass silage (GRAM) and leguminosae-based grass silage (LEG), in accordance with their different required N fertilisation amounts.

Table 8. Comparison of N_2O emissions from analysed farm fertilisation and from standard fertilisation according to the KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.) [21].

	Unit	GRAM *** Silage	LEG *** Silage	Maize Silage	Barley	Triticale	Wheat
Emissions from analysed farms	kg N_2O-N t^{-1} DM	0.277	0.019	0.185	0.238	0.195	0.249
Reference values *	kg N_2O-N t^{-1} DM	0.247 **	0.021	0.167	0.202	0.182	0.383

* [21]. ** Standard fertilisation includes organic fertiliser. For other crops, it includes only chemical fertilisers. *** GRAM denotes gramineae-based grass silage and LEG denotes leguminosae-based grass silage.

The mean value of N_2O emissions released directly into the atmosphere from GRAM using both organic and chemical N fertilisers was 0.277 kg N_2O-N t^{-1} DM, which was slightly higher than the reference value of 0.247 kg N_2O-N t^{-1} DM, which relied only on CAN as chemical fertiliser. Data on N_2O soil emissions alone are present in the current literature; calculations usually consider total GHG emissions. A study by Larsson et al. [45] that experimentally estimated field GHG emissions from GRAM and LEG at different N fertiliser doses cited results very close to those obtained in the present study: in particular, 0.263 kg N_2O-N t^{-1} DM for GRAM at the highest N dose (150 kg N ha^{-1}) and 0.0132 kg N_2O-N t^{-1} DM for unfertilised GRAM, which compare well with the value we obtained for the very low N fertilisation required for alfalfa silage. Maize silage direct N_2O emissions

were about 33% lower than those obtained for GRAM, which verified the previous results in terms of N_2O emissions for the grass-based and maize- and grass-based milking cow diets.

Among the cereals, the lowest N_2O emissions were from triticale, as can be expected due to its lower N needs. Barley and wheat were at values of 0.238 and 0.249 kg N_2O-N t^{-1} DM, respectively, which closely approximated each other. According to the KTBL [21], standard fertilisation for wheat is very high, and the value they provide did not compare well with the value we calculated, as the KTBL considered N fertilisation specifically for wheat used for bread production.

3.4. N_2O Emission Estimation for the Analysed Farms

The N_2O emissions for all analysed farms, expressed as kg CO_{2eq} kg^{-1} ECM, are shown in Figure 5. Total emissions per farm included both milking cows' and younger animals' (heifers and calves) emissions, together with emissions associated with the off-farm concentrate production. The values for the single farms ranged between 0.11 and 0.29 kg CO_{2eq} kg^{-1} ECM (mean value 0.18 ± 0.04 kg CO_{2eq} kg^{-1} ECM), with the lowest values observed in the farms in the central region due to the substitution of permanent grassland with leguminosae crops, except for farm C2, which had a quite high amount of grass silage in the diet and high chemical fertilisation. The highest values were concentrated in the southern region, in particular farms S8 and S11, the two farms with the lowest milk production (16 kg ECM an^{-1} day^{-1}); furthermore, farm S8 employed solid manure as organic fertiliser, which is characterised by higher N_2O emissions compared to slurry [1].

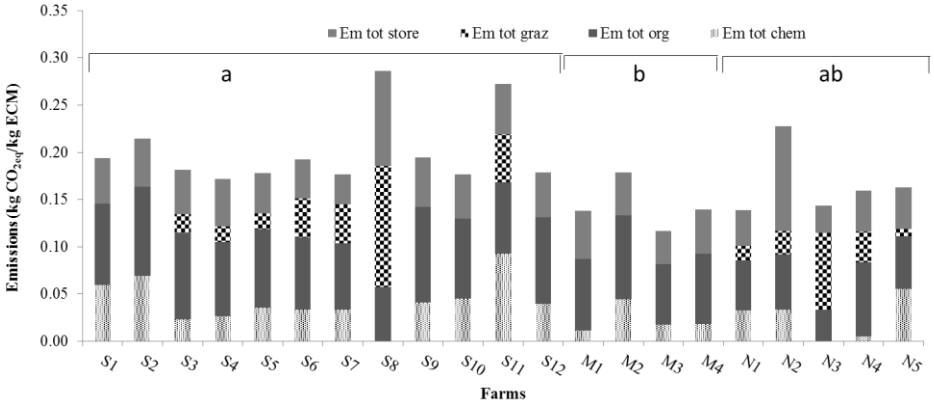


Figure 5. Total N_2O emissions, expressed as kg CO_{2eq} kg^{-1} ECM, calculated per farm and grouped as storage, grazing and organic and chemical fertilisation. Regions are specified as south (S), central (C) or north (N). Letters at the top of the bars show significant differences among the mean values per region ($\alpha = 0.05$).

Compared to other studies, these German farm results are in line with the usual range for dairy farms in northern Europe, as reported by Kristensen et al. [46] (between 0.1 and 0.4 kg CO_{2eq} kg^{-1} ECM) and Bonesmo et al. [9] (0.11 to 0.41 kg CO_{2eq} kg^{-1} ECM).

Nitrous oxide emissions from fertilisation averaged 60% of total N_2O emissions and were as high as 70% in the farms without pasture. On the farms where cows and heifers grazed most of the year (S8 and S11), emissions expressed per kg ECM were particularly higher (0.19–0.27 kg CO_{2eq} kg^{-1} ECM), due to the lower milk production (around 16.0–16.5 kg ECM an^{-1} d^{-1}) [47]. However, a different scenario emerged when considering emissions per unit cultivated surface, which were significantly lower for all farms with large grazing surfaces and high pasture use.

The N_2O emissions from fertiliser storage were at most 30% of total N_2O emissions. Only two farms had higher values, S8 (35%) and N2 (49%), likely due to their use of solid manure as organic fertiliser, the $EF_{storage}$ of which is nearly twofold that of the liquid slurry distributed on the other farms. Transitioning to a slurry-based management system would reduce the N_2O emissions from storage in these instances by 40%.

The effect of concentrates was highly variable among the farms. Concentrates had a share in the milking cow diets between 15 and 30%; the emissions originated by the concentrates ranged between 9 and 19%. In just one farm, where the milking cow diets were based almost totally on grass silage and pasture (S6), the amount of concentrate in the milking cow diet was really low, about 4%, but this had no particular effect on the total N_2O emissions of the farm.

An analysis of total farm N_2O emissions per unit of milk demonstrated a significant difference between southern farms (0.20 kg CO_{2eq} kg^{-1} ECM) and central ones (0.14 kg CO_{2eq} kg^{-1} ECM). The same analysis failed to highlight any significant difference when only milking cow emissions were considered. This result is interesting because it highlights two different aspects of the analysis of the farm data. The first aspect is that despite the large non-uniformity of the selected farms in terms of dimensions, management systems, weather conditions, manure management and fertilisation, the N_2O emissions remained very comparable, except for a few cases, such as S8 and S11, where the milk production was very low (less than 6000 kg ECM an^{-1} y^{-1}). The second aspect is the relevance/importance of collecting detailed farm-scale data on the number of young animals—heifers in particular—and their management when estimating N_2O emissions: milking cow characterisation alone is inadequate, not only for calculating total emissions, but also when other parameter effects need unmasking. The contribution of the heifers in terms of N_2O emissions in the analysed dairy farms ranged between 12 and 32% and was correlated primarily with the length of the reproductive cycle (R^2 = 0.61). The heifer management in the dairy farms was not as standardized as for the milking cows and was always strictly linked to pastures when they were present on the farm; for this reason, this contribution can make a large difference in the farm N_2O emissions.

3.5. Effects of Management Conditions on N_2O Emissions

3.5.1. Emission Sources

The principal N sources for dairy farms were organic fertilisers (slurry and solid manure), which together typically represented more than 70% of N supplied to crops.

Concerning chemical fertilisers, according to the reported gas emissions factors, the CAN-derived N_2O emissions were slightly higher than those from NP because of the lower EF_{NH3} and the consequent higher amount of N as a source for the N_2O emissions [3]. The substitution of NP or CAN with urea would reduce N_2O emissions by 11.6% or 10.9%, respectively. For the same amount of N spread on the field, the use of NP or urea might thus be a way to mitigate the N_2O emission to the atmosphere, as also reported in other studies [48,49]. A limitation of such a mitigation strategy would, however, be the higher NH_3 emissions.

3.5.2. Effect of Single Parameters

The manure management was shown to differentiate N_2O emissions. The use of solid manure, as opposed to liquid slurry, was clearly correlated to the total N_2O emissions. In general, when solid manure was employed instead of slurry (farms S8 and N2), storage N_2O emissions were more than doubled: as a consequence, even if N_2O emissions after solid manure application were slightly lower due to higher ammonia losses, total N_2O emissions from solid manure were definitely higher than from slurry.

The diet composition was found to strongly affect the total N_2O emissions of dairy farms. Statistical model results indicated that the ratio between the percentage of grass and maize in the diets had the largest power to predict total N_2O emissions on a farm (p = 0.0002, R^2 = 0.56). Figure 6 shows that diets rich in grass increased N_2O emissions on the dairy farms, whereas maize-based diets reduced N_2O emissions, which is in agreement with previous results [9,46,50]. For instance, for a unitary decrease of the grass/maize ratio (e.g., from 2:1 to 1:1), the expected reduction in N_2O emissions equals the slope of the regression line, i.e., −0.025 kg CO_{2eq} kg^{-1} ECM, which, referenced to the grand mean of 0.18 kg CO_{2eq} kg^{-1} ECM, means an average relative reduction of about 14% per

unitary ratio change. The protein content of the diet was also well-correlated with the N_2O emissions in the dairy farms ($p = 0.0002$, $R^2 = 0.52$).

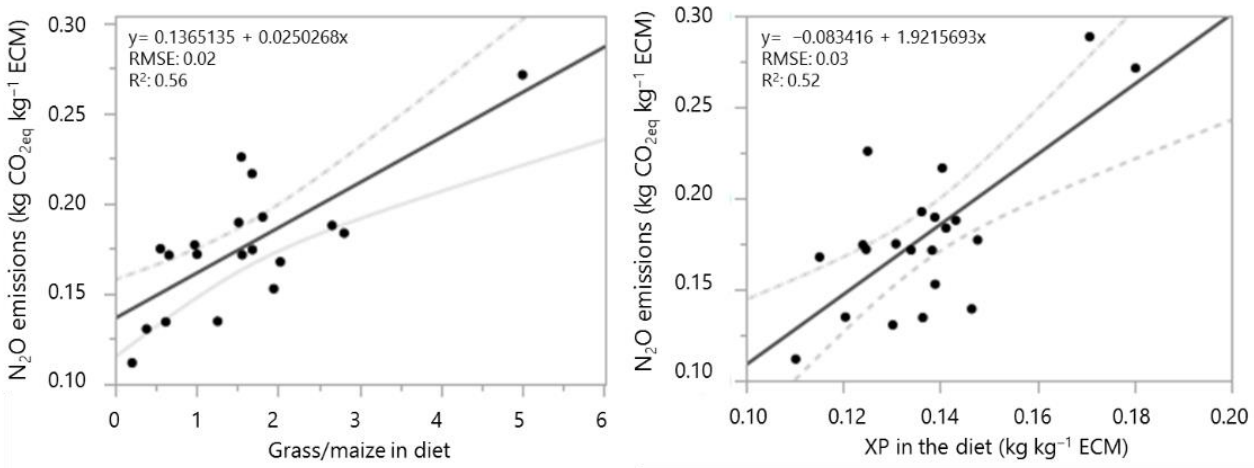


Figure 6. Effects of the grass/maize ratio and of the diet protein content (XP) on N_2O emissions from the analysed dairy farms, expressed as t CO_{2eq} ha^{-1} per year.

These two parameters, diet protein content and the grass/maize ratio of the diet, were also well-correlated with each other ($R^2 = 0.49$) because of the high protein content of the grass (15–20% of DM). These results confirm those obtained in other studies [51,52], where the large contribution of the diet protein content of the cattle on the N_2O emissions of the farms was reported.

The quantity of nitrogen fertiliser per hectare (kg N ha^{-1}) used for the cultivation of the feedstuffs was found to not be correlated with the total N_2O emissions in the analysed farms (total fertilisation per hectare, $R^2 = 0.0003$; organic fertilisation per hectare, $R^2 = 0.0142$). The absence of correlation between the fertiliser amount and the N_2O emissions was probably due to the high contributions of the grazing and the manure management on the total farm N_2O emissions [53]. In order to produce evidence of the effect of the fertiliser, it was necessary to create a prediction model, which also included these two parameters as nominal factors.

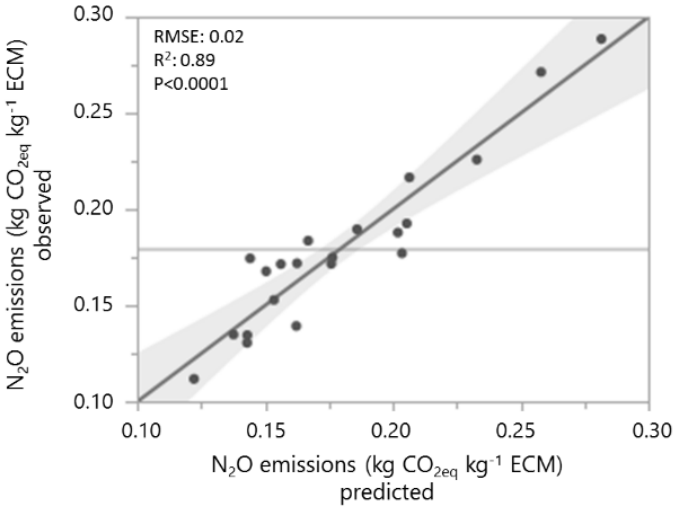
3.5.3. Linear Prediction Model

A higher predictive power can be obtained by composing a multilinear model with more predictors. Among all considered combinations of farm management parameters, the best choice was a model containing the manure type x_{man} (0 = liquid, 1 = solid), the dietary crude protein content XP, the total nitrogen fertilisation $(N_2O\text{-}N)_{fert}$ and the organic fertilisation $(N_2O\text{-}N)_{org}$ as predictors. The regression results with only these variables are shown in Figure 7. This model offers a high coefficient of determination ($p < 0.0001$, $R^2 = 0.89$) with a reduced set of parameters. The resulting prediction equation is then:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_{man} \cdot x_{man} + \hat{\beta}_{XP} \cdot XP + \hat{\beta}_{fert} \cdot (N_2O\text{-}N)_{fert} + \hat{\beta}_{org} \cdot (N_2O\text{-}N)_{org} \quad (9)$$

with the regression coefficients reported in Figure 7. Although the total and the organic nitrogen fertilisation were highly correlated ($R^2 = 0.91$), they were both included in the model because their information content did not completely overlap; in that sense, the negative coefficient of the organic fertilisation should not be interpreted as a negative effect but as a correction factor of the total fertilisation in the linear model.

As discussed in Section 3.4, the analysis of the emissions calculated on the base of farm management data showed the importance of also collecting information about the younger animals in order to highlight in more detail the differences between the farms.



Summary of Fit

RSquare	0.890102
RSquare Adj	0.862627
Root Mean Square Error	0.016134
Mean of Response	0.179539

AICc	BIC
−101.441	−101.174

Variance Analysis

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.03373361	0.008433	32.3973
Error	16	0.00416499	0.000260	**Prob > F**
C. Total	20	0.03789860		<0.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	−0.088	0.037	−2.38	0.0298
Sol/Liq man	0.084	0.013	6.48	<0.0001
XP Diet	1.508	0.252	5.97	<0.0001
Total N Fert	0.0003	0.0001	4.33	0.0005
Org N Fert	−0.0004	0.0001	−2.86	0.0114

Figure 7. Effects of the dairy farm parameters (manure type, solid or liquid manure (Sol/Liq man), crude protein content (XP Diet), total nitrogen fertilisation (Total N Fert) and organic nitrogen fertilisation (Org N Fert)) on the total N_2O emissions, expressed as kg CO_{2eq} kg^{-1} ECM.

4. Conclusions

The estimation of the direct N_2O emissions associated with milk production on the basis of farm management data yielded values between 0.11 kg and 0.29 kg CO_{2eq} kg^{-1} ECM. Different dairy farm management systems can determine a quite large range of N_2O emissions. Farms with animal diets mainly based on leguminosae and maize silage and a limited nitrogen fertilisation showed lower N_2O emissions; on the contrary, farms with solid manure management and animal diets mainly based on grass showed higher N_2O emissions.

A linear model that included the protein content of the animal diet, the amount and type of fertiliser, as well as the manure management (liquid or solid), enabled the prediction of about 89% of the direct N_2O emissions. In the absence of detailed information on the animal diet, just the grass-to-maize ratio as a single parameter made it possible to estimate 56% of the farm N_2O emissions. The data on the nitrogen fertilisation in the farm (total and organic fertiliser per hectare) alone could explain less than 2% of the N_2O emissions. With the more sophisticated approach, an instrument can be offered to consultants, rapporteurs and decision makers for the analysis of the environmental impact of different dairy farms or different farm management strategies and the effects of emission mitigation strategies, based on farm data which are available or can be easily obtained.

The variability in heifer rearing was larger than in the management of the milking cows. Thus, the N_2O emissions from heifer rearing ranged between 12 and 32% of the whole emissions. This underlines that heifer rearing has to be included in the estimation of the N_2O emissions of dairy farms.

The present study showed that not just the type of chemical fertiliser and the manure management but also the diet composition can mitigate N_2O emissions. Using urea instead of CAN and NP fertilisers could reduce the whole N_2O emissions by 11%, but at the cost of higher ammonia emissions. By substituting solid manure with liquid slurry, an emission reduction of about 40% could be achieved. A reduction of the grass-to-maize ratio, from 2:1 to 1:1, could decrease the whole N_2O emissions by 14%.

The findings of this study are based on data from the literature and 21 farms from three German regions investigated over a period of two years. This highlights a limitation of the performed tests and the linear models. The validity of the tests and models could be increased by the inclusion of data from more farms in further regions in the analyses.

Future research could be focused on further models for the calculation of N_2O emissions, other cropping conditions (fertilisation, yields) and other farm types (e.g., cattle or pig fattening, poultry farms). In this way, knowledge about the most important data to estimate N_2O emissions, e.g., for emission inventories, and about the mitigation potential in the different sectors of a dairy farm, especially in the diet composition and feed cropping sectors, can be expanded. In this way, farmers can obtain advice on how to reduce GHG emissions. Furthermore, the effects of changing cropping or climatic conditions on farm-related N_2O emissions can be estimated better than before.

Author Contributions: Conceptualization, W.B.; Methodology, W.B., S.M., G.L.; Validation, S.M.; Formal Analysis, S.M., G.L.; Investigation, S.M., W.B.; Resources, S.M., W.B.; Data Curation, S.M.; Writing—Original Draft Preparation, S.M.; Writing—Review & Editing, W.B., G.L., S.M.; Visualization, S.M.; Supervision, S.M., G.L., W.B.; Project Administration, W.B.; Funding Acquisition, W.B. All authors have read and agreed to the published version of the manuscript.

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