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Gaseous emissions arising from protein production with German Holsteins – an analysis of the energy and mass flows of the entire production chain 2. Emissions and reduction potentials

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Abstract

This study analyses reduction potentials of greenhouse gas and ammonia emissions in protein production with cattle herds using a sensitivity analysis leading to scenarios for practical agriculture. In particular, the effects of varied productive lifespans (number of lactations), diseases and animal losses, increased performance (milk yield, daily weight gain), amounts and types of mineral fertilizers applied, manure management (here restricted to biogas plants) were considered, as these measures are within the range of actions of a farmer and feasible. The survey describes a herd of 100 German Holstein cows with their offspring under steady state conditions. The absolute emissions of the herd as well as the protein-related emissions are quantified

Despite the fact that the main emission sources (for greenhouse gases: methane from enteric fermentation, for ammonia: emissions from animal houses) can hardly or not be altered, the effects reflecting improved production factors have a significant effect if combined. Thus, they may more than compensate the increased emissions resulting from the likely increase in milk yields in the next decade. Measures evaluated result in reduced production areas, decreased nitrogen surpluses, improved nitrogen efficiencies and reduced emissions per unit of product (edible protein) – without additional expenses.

Keywords: *dairy cattle, protein, emissions, greenhouse gases, ammonia*

Zusammenfassung

Gasförmige Emissionen bei der Eiweißerzeugung mit Deutschen Holsteins – eine Analyse der Energie- und Stoffflüsse der gesamten Produktionskette 2. Emissionen und deren Minderungspotenziale

Möglichkeiten zur Minderung von Treibhausgas- und Ammoniak-Emissionen bei der Eiweißproduktion mit Holstein-Rindern werden in einer Sensitivitätsstudie untersucht und in praxisnahen Szenarien zusammengefasst. Untersucht werden die Einflüsse der Nutzungsdauer der Milchkühe und der Krankheitsinzidenzen, von Leistungssteigerung, Mineraldüngermengen und -arten sowie vom Wirtschaftsdüngermanagement – Maßnahmen, die im Entscheidungsbereich des Halters liegen und machbar erscheinen. Untersucht wird eine Herde mit 100 Holstein-Milchkühen mit ihren Nachkommen im Fließgleichgewicht. Die absoluten Emissionen der Herde und die auf die Eiweißproduktion der Herde bezogenen Größen werden bestimmt.

Auch wenn die Hauptquellen (Methan aus der Verdauung und Ammoniak aus dem Stall) nicht oder kaum beeinflusst werden können, so addieren sich die Minderungen aufgrund verbesserter konventioneller Produktionsfaktoren bemerkenswert auf: Sie können die Mehremissionen aus der in den kommenden 10 Jahren zu erwartenden Leistungssteigerung (Milchleistung) mehr als kompensieren, führen zu verringerten Anbauflächen, verringerten Stickstoffüberhängen und zu einer erhöhten Stickstoffeffizienz bei weiter reduzierten Treibhausgas-Emissionen je kg verzehrbarem Eiweiß - ohne finanziellen Mehraufwand.

Schlüsselwörter: *Milchkühe, Protein, Emissionen, Treibhausgase, Ammoniak*

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1 Introduction

In 2013, about 12.6 million cattle, including nearly 4.2 million dairy cows, were kept in Germany. These herds produced almost 32 million tons of milk. The predominant breed, in particular in the Northern German federal states, is German Holstein (about 56 % of dairy cows, StatBA, 2014). Beef from cows and from the fattening of offspring is produced jointly with milk production. The economic significance of milk and beef production is considerable: about 40 % of the aggregate value added in German agriculture originates from cattle farming (Brade, 2006).

Cattle farming provides additional social benefits. The German landscape is profoundly influenced by livestock husbandry, and people like the open cultivated land with grazing animals. Pastures are also an important element in maintaining species diversity and nature conservation (Brade, 2012). Carbon sequestration is not an issue that arouses public interest, unlike landscape. However, pastures are a significant repository of carbon. Milk, dairy products and beef are sources of high quality protein whose composition is favourable to the human metabolism. They also contain valuable other nutrients (vitamins, minerals). The specific role of cattle as ruminants in human nutrition is their ability to exploit plants as fodder that are not suitable for direct human consumption.

On the other hand, cattle farming is a major source of greenhouse gas (GHG) emissions, in particular of methane (CH_4) and nitrous oxide (N_2O) and of reactive nitrogen species such as ammonia (NH_3) and nitric oxide (NO). CH_4 is produced by microbial degradation of organic matter under anaerobic conditions both in the digestive tract of cattle and during manure storage. N_2O is formed from the microbial and chemical transformation of nitrogen (N) compounds, both in oxidizing (nitrification) and reducing reactions (denitrification). N_2O formation is almost always associated with NO and di-nitrogen (N_2) emissions. NH_3 is released during the entire manure management chain, almost exclusively from the urine excreted.

Emissions occur from the entire production chain, and in principle they are to be allocated to the specific product the society requires. This includes not only emissions from the provision of animal feeds, but also from the use of machinery and from the fuels needed to produce fertilizers.

In this paper we attempt to make a comprehensive investigation in mass flows and the concurrent emissions in a cattle herd with milk and beef production, and relate emissions to the product: protein. ***To our knowledge this paper is the first attempt to simultaneously quantify the GHG and NH_3 emissions of an entire herd and the complete production chain and establish the respective protein related footprints.***

This also allows for a valuation of emission reduction steps in cattle husbandry.

The reference farm, line of action and initial assumptions

- A reference dairy farm is defined reflecting the present situation in Northern Germany as well as possible. This farm keeps 100 dairy cows [1] and their offspring. [2] Mean milk yield is 8000 kg cow^{-1} $lactation^{-1}$.[3] Three lactations are assumed. Animal losses and diseases are considered to be on a moderate level. Animals are loose-housed in a conventional building producing slurry. A typical diet is fed. [4]
- This farm produces all feeds required using the livestock manures as a source of crop nutrients. In Germany, increasing amounts of slurry are used to produce biogas. On the reference farm, 20 % of the slurry is used as a biogas feedstock (which reflects current practice, see Haenel et al., 2016).
- The use of mineral fertilizers is restricted by German legislation (Düngeverordnung, BMELV DüV, 2007). Recommendations take yields into account and provide a default amount of 60 kg ha^{-1} a^{-1} N to cover losses to the atmosphere and to surface and ground waters (DüV, § 9). [5] The scenario reflecting current practice makes use of the maximum amounts allowed. Manure N from cattle spread as slurry is lost to the atmosphere (about one third). Of the amount entering soil about one third is liable to be lost to surface and ground waters (IPCC, 2006). As a result, the German fertilizer enactment recommends to take 50 % of the amount applied when quantifying the amount of mineral fertilizer.
- The reference farm is not considered to use legume-based pastures. Also, atmospheric N deposition is not considered for the reference farm (which reflects current fertilizing practice).
- In subsequent steps, single input parameters are varied, as shown in Table 1. The reduction potentials of such alterations are assessed *line by line*. All variables in the other lines are standard. No combinations are taken into account.
- Finally, scenarios deal with combined measures that are likely to reduce GHG and NH_3 emissions significantly.

Our model calculations do not include changes in milk quality such as fat and protein contents or meat quality. Manipulations of the rumen biome are not considered. The assumptions in Table 1 describe potential situations irrespective of their present likelihood.

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[1] This reflects the current situation on modern dairy farms in Northeast Germany (StatBA, 2014)

[2] For dairy cows both milk and meat production is taken into account. Female offspring are mainly reared for reproduction of the dairy herd; male animals are fattened in the animal house producing comparatively heavy carcasses. For these animals grazing occurs very rarely and is not considered. It is uncommon in northern Germany to castrate male animals.

[3] In 2012 the mean German milk yield was 7280 kg $animal^{-1}$ a^{-1}. For the German Holstein region with Nordrhein-Westfalen, Niedersachsen, Schleswig-Holstein, Brandenburg and Mecklenburg-Vorpommern 7552, 7653, 6976, 8414 and 8412 kg $animal^{-1}$ a^{-1}, respectively, were reported.

[4] See appendix 1 in Dämmgen et al. (2016)

[5] 60 kg ha^{-1} a^{-1} approximately cover losses of 10 % to NH_3-N, 1 % to N_2O-N, 1 % to NO-N and 3 % to N_2 as well as 10 % to surface and ground waters, if the fertilizer (present German mix) is applied in to growing plants, using several adequate shares of the total, according to plant nutrition requirements.

Table 1
Input parameters varied in our calculations (see text above)

entity varied	unit			reference farm			
milk yield	kg cow^{-1} lactation^{-1}		7000	**8000**	9000	10000	11000
final weight bulls	kg animal^{-1}		550	**675**			
final weight beef heifers	kg animal^{-1}		435	**535**			
losses	% of cows in 1st lactation		5	**10**	20		
productive lifetime	lactations cow^{-1}			**3**	4	5	
grazing	% of vegetation period			**0**	100		
mineral fertilizer applied	% of recommended amount	80	90	**100**			
additional fertilizer (above recommendation)	kg ha^{-1} a^{-1} N			**60**			
solid urea	% of total mineral fertilizer		0	**37**			
grass clover mixture	% of total grass fed			**0**	50		
deposition	kg ha^{-1} a^{-1} N			**0***	10**		
biogas	% of slurry produced			**20**	60	100	
manure to arable land,							
trailing hose, incorp. within 1 h	% of slurry produced			**0**	45		
trailing hose, incorp. within 4 h	% of slurry produced			**45**	0		
injection	% of slurry produced			**5**	5		
manure to grassland							
broadcast	% of slurry produced			**45**	5		
trailing shoe	% of slurry produced			**5**	45		
injection	% of slurry produced			**0**			

* 0 indicates N deposited from the atmosphere is not taken into account when fertilizer amounts are calculated
** indicates that N deposition of from the atmosphere of 10 kg ha^{-1} a^{-1} is taken into account when N fertilizer amounts are calculated

Calculation methodology
The methods used in this study are described in detail in Dämmgen et al. (2016). They comprise calculations of emissions from animal metabolism, manure management, feed production, provision of mineral fertilizers and lime as well as of water and energy (diesel, natural gas, electricity).

2 Animal numbers related to the number of lactations and animal losses

The entire herd is assumed to be in steady state, so that animal numbers within categories remain constant with time. If a dairy cow is lost, it is immediately replaced by a young cow that had just given birth to a calf. Hence the number of dairy cows is kept constant in any case, whereas the numbers of animals in the other sub-herds are related to the number of lactations per cow and the rate of animal losses. Table 2 collates the overall losses resulting from high, medium and moderate loss rates. Tables 3 and 4 give the numbers of animals to be fed. As our model herd is hypothetical, fractions of animals can be considered.

Conclusion: Decreasing losses of dairy cows result in a more even distribution of animal numbers among lactations. The share of animals in the 1st lactation is reduced. Hence the whole herd produces more milk (see Tables 5 and 6).

Table 2
Animal losses in dairy herds

	overall losses due to slaughtering and perishing			useful fraction (slaughtered animals)
	high losses animal animal^{-1}	medium losses animal animal^{-1}	moderate losses animal animal^{-1}	animal animal^{-1}
dairy cows, 1st lactation	0.20	0.10	0.05	0.92
dairy cows, subsequent lactations	0.07	0.05	0.03	0.92
calves (all)	0.15	0.10	0.08	0.0
female calves	0.12	0.07	0.06	0.0
male calves	0.18	0.13	0.10	0.0
dairy heifers	0.01	0.01	0.01	0.6
beef heifers	0.03	0.02	0.02	0.6
beef bulls	0.06	0.05	0.04	0.6

Table 3
Numbers of dairy cows fed and milked as a function of the number of lactations, high, medium and moderate losses

overall number of lactations	losses	animal herd^{-1} lactation 1st	2nd	3rd	4th	5th	Total
3	high	39.3	31.4	29.2			100.0
	medium	36.3	32.7	31.0			100.0
	moderate	34.8	33.1	32.1			100.0
4	high	30.9	24.7	23.0	21.4		100.0
	medium	28.0	25.2	24.0	22.8		100.0
	moderate	26.6	25.2	24.5	23.7		100.0
5	high	25.8	20.6	19.2	17.8	16.6	100.0
	medium	23.0	20.7	19.7	18.7	17.8	100.0
	moderate	21.6	20.5	19.9	19.3	18.7	100.0

Table 4
Numbers of animals fed other than dairy cows as a function of the number of lactations, high, medium and moderate losses

overall number of lactations	losses	animal herd^{-1} female calves	male calves	dairy heifers	beef heifers	beef bulls
3	high	50.6	49.0	46.4	0.5	45.3
	medium	49.9	48.3	39.2	8.5	45.5
	moderate	49.3	47.8	36.2	11.5	45.5
4	high	50.2	48.6	36.8	10.1	44.8
	medium	49.7	48.1	30.3	17.4	45.3
	moderate	49.3	47.7	27.4	20.3	45.5
5	high	49.9	48.3	30.5	16.3	44.6
	medium	49.6	48.0	25.0	22.7	45.2
	moderate	49.2	47.7	22.5	25.2	45.4

With increasing numbers of lactations, the number of non-productive animals (i.e. those animals that do not produce marketable protein; calves, dairy heifers) decreases, the overall number of productive animals (beef heifers and bulls) increases, although there is a reduction in bull numbers.

Selective breeding relies on surplus heifers. With lactation numbers < 3, every heifer has to be used for milk production. Selection for higher milk yields etc. is impossible.

3 Protein production of the entire herd in relation to the overall numbers of lactations and to animal losses

Typical milk yields in the 1st lactation are less than those of subsequent lactations. We therefore define a nominal milk yield as the mean of the first three lactations, as listed in Table 5.

An increasing number of lactations increases the amount of milk protein produced. However, the amount of meat protein decreases as the animal numbers in all sub-herds decrease (Tables 3 and 6). The share of meat protein also decreases. Reduced animal losses result in increased overall amounts of protein, in particular due to increased numbers

Table 5
'Nominal milk yields' (average of first three lactations) as opposed to real milk yields in different lactations (in kg animal^{-1} lactation^{-1})

nominal milk yield	7000	8000	9000	10000	11000
real milk yield					
1st lactation	6300	7200	8100	9000	9900
subsequent lactations	7350	8400	9450	10500	11550

Table 6

Amounts of protein produced in a herd with a nominal milk yield of 8000 kg animal^{-1} lactation^{-1} as a function of the number of lactations as well as high, medium or moderate losses

overall numbers of lactations	losses	Mg herd^{-1} lactation^{-1} protein						share of meat protein %
		milk	slaughtered cows	utilized dairy heifers	slaughtered beef heifers	slaughtered beef bulls	total	
3	high	24.6	2.27	0.00	0.02	2.12	29.0	15.2
	medium	24.7	1.99	0.00	0.34	2.17	29.2	15.4
	moderate	24.8	1.88	0.00	0.46	2.19	29.3	15.4
4	high	25.0	1.78	0.00	0.40	2.10	29.3	14.6
	medium	25.1	1.53	0.00	0.69	2.17	29.5	14.9
	moderate	25.2	1.43	0.00	0.80	2.19	29.6	14.9
5	high	25.2	1.49	0.00	0.64	2.09	29.4	14.3
	medium	25.3	1.25	0.00	0.90	2.16	29.6	14.6
	moderate	25.4	1.16	0.00	1.00	2.19	29.7	14.6

of beef heifers. Table 6 summarizes the results for a herd with a nominal milk yield of 8000 kg animal^{-1} lactation^{-1}.

Conclusion: Extended productive lifespans of dairy cows result in moderately increased amounts of protein produced. The increase in milk protein more than compensates for the losses in meat protein. Reduced losses also result in increased protein yields – a rather small effect that should nevertheless be taken into account.

4 Sources of emissions from protein-production with dairy herds

4.1 The locations

The emissions are considered to originate from animal and microbial metabolism (CH_4 from enteric fermentation), from managed manures (in the house or during grazing, during storage or within a biogas plant, during or after application), from plant production (crops, grass), from the production of mineral fertilizers and lime (soil sweetener (ameliorant), animal feed lime), production processes during related industrial processes (e.g. production of rapeseed extraction meal or sugar beet shreds) as well as from the provision of other working materials (water, diesel, natural gas) and electricity.

Figures 1 and 2 illustrate the origins of GHG and NH_3 emissions for the reference herd, both for housed-only animals and for a herd in which dairy cows are grazed during the growing season (dairy cows 10 h d^{-1}). Dairy heifers are grazed all day during the second vegetation period in their lifespan. A complete list of emissions is provided in the Appendix.

Figure 1 illustrates the extent to which GHG emissions are dominated by CH_4 from enteric fermentation. Major

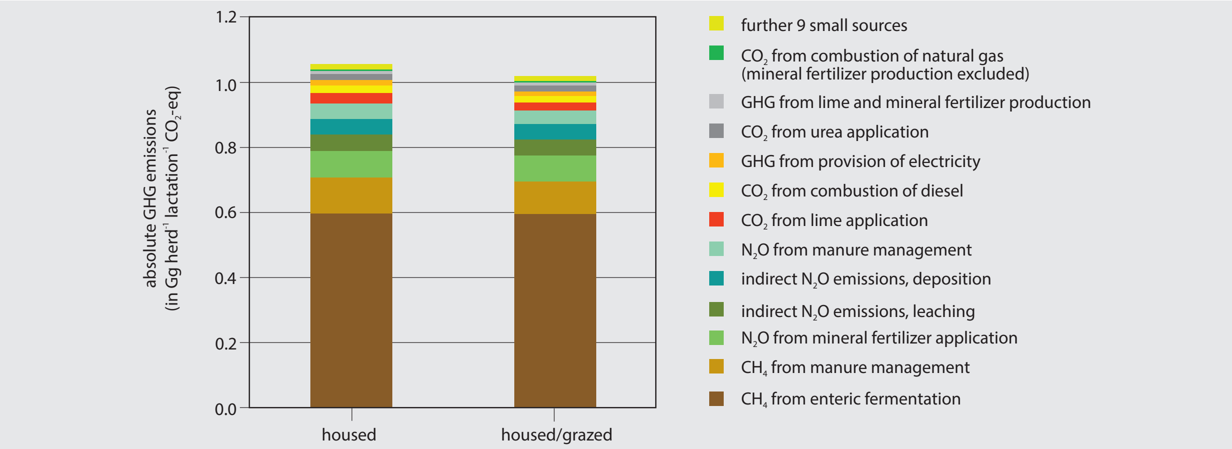

Figure 1

GHG emissions from dairy cow herds producing 8000 kg animal^{-1} lactation^{-1} (current practice, either housed only or grazed during the growing season), sorted according to importance with respect to overall emissions (further nine sources are: CH_4 emissions from storage of silage, from excreta during grazing, from non-marketable milk during manure storage and from the combustion of natural gas; N_2O from the combustion of diesel and natural gas (except emissions from fertilizer production) as well as from storage of silage and non-marketable milk; CO2 from lime in feed) sources that can be influenced by management practices are direct CH_4 emissions resulting from manure management [6] and indirect N_2O emissions. [7] Grazing reduces CH_4 emissions from manure management, as any VS dropped on the pasture will decompose mainly aerobically.

For NH_3, more than a third of the emissions is apportioned to manure application, plus a quarter each to emissions from the livestock building and from mineral fertilizer application (Figure 2). Here, the share of solid urea is considerable. (37 % of the mineral fertilizer used on the reference farm is solid urea.) Mineral fertilizer production contributes 3.8 % (housed) and 3.5 % (housed and grazed), respectively. Emissions from silage losses and the share of emissions that is attributed to non-marketable milk (emitted with slurry) are of minor importance.

Grazing requires additional energy to obtain food which results in increased excretion rates. It should be kept in mind that the grazing of dairy cows definitely reduces NH_3 emissions from the animal house and the subsequent manure management. The additional dark green bar in Figure 2 (housed/grazed) for emissions from the pasture is small, as urine infiltrates rapidly causing NH_3 emissions that are small in comparison with those in the house. However, as bulls and heifers for fattening are housed at all times, the overall effect is minor.

Emissions from silage losses are small but unavoidable. At least partly avoidable emissions resulting from discharged contaminated milk are negligible.

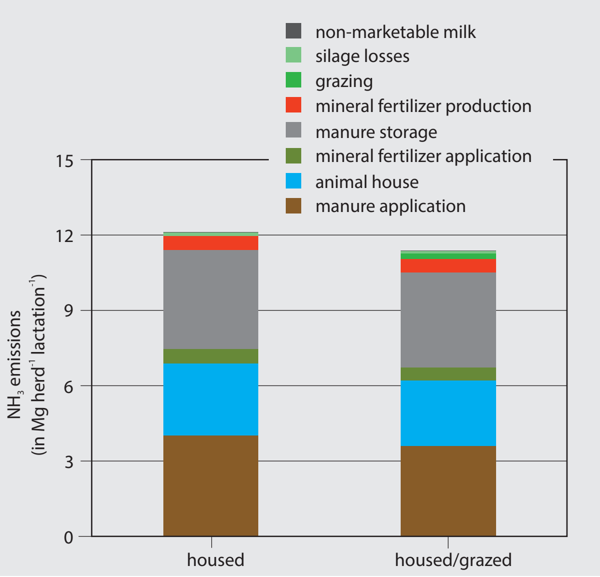

Figure 2
NH_3 emissions from dairy cow herds, nominal milk yield 8000 kg cow^{-1} lactation^{-1} (left bar: no grazing apart from dairy heifers; right bar: all dairy cows grazed 10 h d^{-1} during the vegetation period, in addition)

4.2 Assignment of emissions to single animal categories

Figures 3 and 4 show CH_4 emissions from enteric fermentation and of NH_3 from manure management as a function of the overall number of lactations. As expected, emissions are dominated by the dairy cow population, which forms more than half of the respective total. The calves' contribution is negligible. With increasing numbers of lactations, the contribution of dairy heifers decreases whereas that of beef heifers increases.

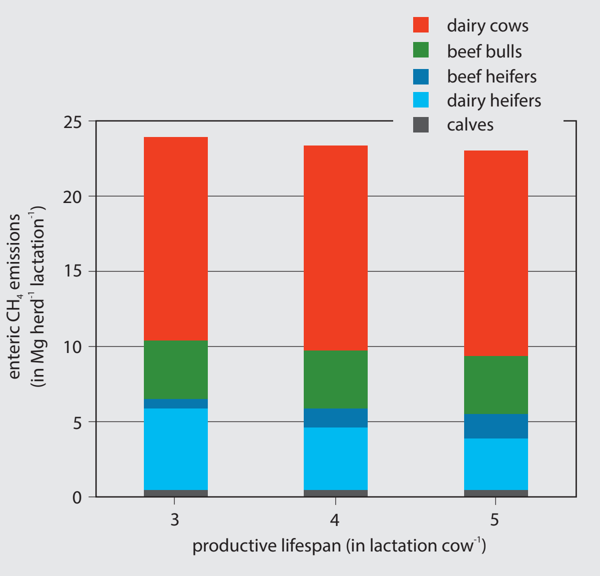

Figure 3
Enteric CH_4 emissions for the respective animal categories, related to the number of lactations per cow (current practice, all other variables as in reference farm, see Table 1)

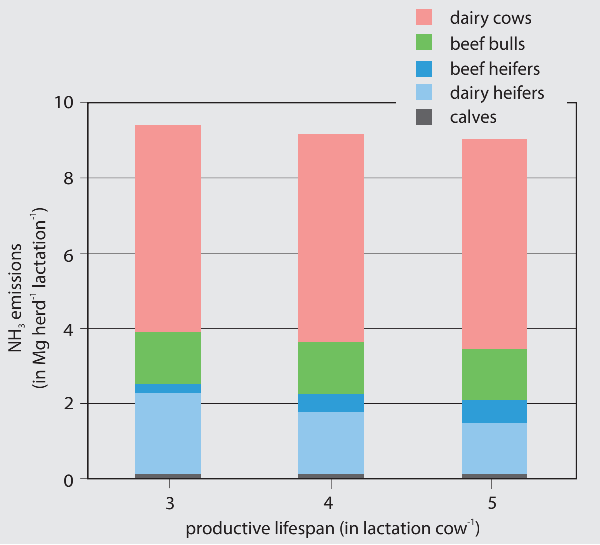

Figure 4
NH_3 emissions of the respective animal categories from manure management (house, storage, application) (current practice, all other variables as in reference farm, see Table 1)

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[6] Assumptions for the reference farm: All animals except calves in slurry-based cubicle house; storage of slurry in tanks with natural crust (biogas: gas tight tanks).

[7] Indirect N_2O emissions result from the transformation of N leached to ground and surface waters and of reactive N deposited after emission from all agricultural sources listed above. For details see Dämmgen et al (2016), Chapter 2.10.

5 Variation of performance and management practices

5.1 Milk yield

As in other businesses, protein production from dairy herds has to aim at the reduction of unit costs in order to be competitive. Here, this can be achieved by increased productivity of the herd, in particular with increasing milk yield per cow and lactation.

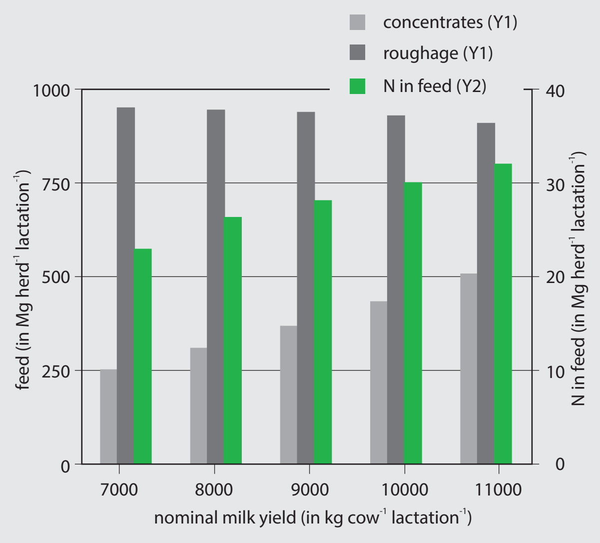

Figure 5

Feed intake of the herds as a function of milk yield. Other variables as in reference farm (see Table 1). Left ordinate: amounts of concentrates and roughage; right ordinate: amounts of N.

5.1.1 Milk yield and feed requirements

With limited capacity of the rumen, higher milk yields presuppose higher energy and nutrient inputs. This can be achieved by increasing the share of concentrates, which is close to 45 % for a milk yield of 11000 kg cow^{-1} lactation^{-1} (e.g. Brade and Brade, 2014). The N intake with feed is almost proportional to the concentrate intake, as illustrated in Figure 5.

5.1.2 Milk yield, N excretion and mineral fertilizer requirements

Inter alia, increasing yields result in extended calving intervals and at the same time in an increased share of the gross energy serving as maintenance energy. As a result, the amounts and composition of excreta are changing. Increased feed requirements lead to increased crop areas to supply the feed. Also, the amount of mineral fertilizers complementing the manures in order to cover the N demands increases, however, its percentage contribution decreases slightly (Figure 6).

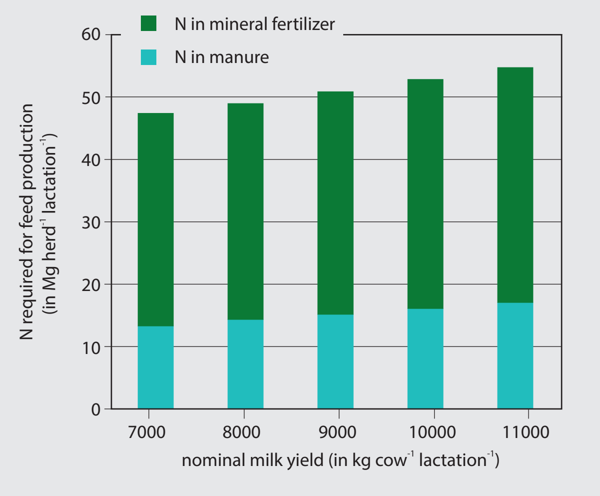

Figure 6

Shares of manure and mineral fertilizer required to meet the N demand of plants as related to milk yields (current practice, all other variables as in reference farm, see Table 1)

5.1.3 Effect of milk yields on the emissions of the entire production chain

Increased animal performance affects energy and nutrient uptake and results in increased emissions *per animal* or *per herd* for the entire production process. However, the share of maintenance energy remains constant (unchanged animal masses). This leads to reduced emissions *per unit of product* (Figures 7 and 8). Absolute GHG and NH_3 emissions increase with performance (about 10 % and 20 %, respectively), but the protein-related emissions decrease significantly (about 25 %).

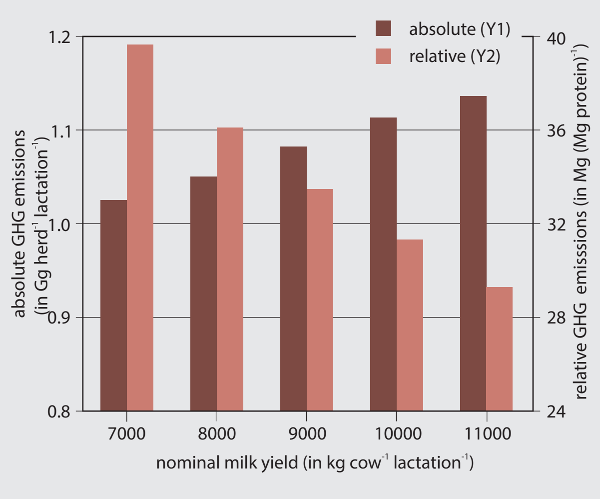

Figure 7

Absolute and protein-related GHG emissions of dairy cow herds as a function of nominal performance (current practice, other variables as for reference farm). Note that axes do not start at origin.

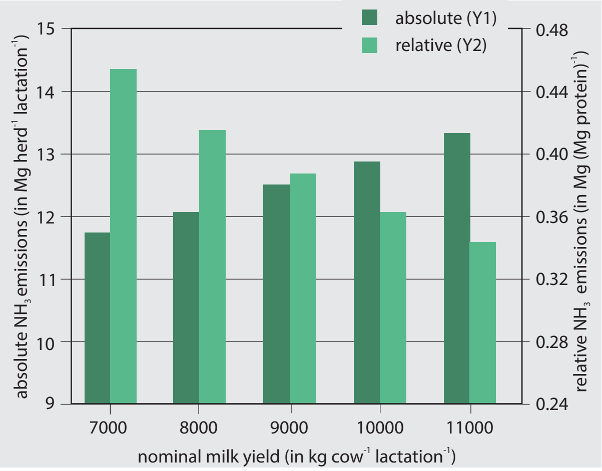

Figure 8

Absolute and protein-related NH_3 emissions of dairy cow herds as a function of nominal performance (current practice, other variables as in reference farm). Note that axes do not start at origin.

5.1.4 Effect of milk yields on the areas for cultivation of feed

With increasing demands for feed, the cultivated area increases. Again, a significant reduction can be observed in relation to the amount of protein produced (Figure 9).

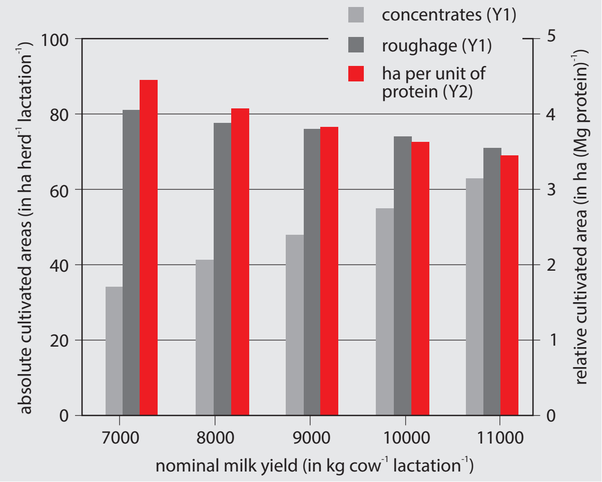

Figure 9

Areas required for feed production of herds with different performances (all other variables as for reference farm). Left ordinate: absolute areas required for roughage and concentrates, right ordinate: areas related to protein produced.

5.1.5 Conclusions

Increased milk yields result in more efficient nutrient utilizations, i.e. transformation into useful products and reduced excretions (N, VS, enteric CH_4) per unit of product. The main reason is the allocation of the maintenance energy over larger amounts of products.

With present annual increases of milk yields[8], a mean of 8500 kg cow^{-1} a^{-1} can be expected in 5 to 7 years. Compared with an 8000 kg cow^{-1} a^{-1}, this increase of about 6 %, which coincides with an increase of absolute GHG emissions of 2 % and almost unchanged NH_3 emissions, leads to a reduction of protein-related GHG emissions by about 3 %. For NH_3 a reduction of about 5 % can be obtained.

5.2 Emission reduction resulting from improved herd management

5.2.1 Effect of reduced animal losses

As stated above, decreased animal losses should result in increased absolute emissions. However, protein-related emissions are likely to drop with decreased animal losses. Reduced losses result in more meat from beef heifers, and fewer cows are slaughtered. The overall beef production remains almost unaffected. (Table 6). Figures 10 and 11 show the results of our calculations.

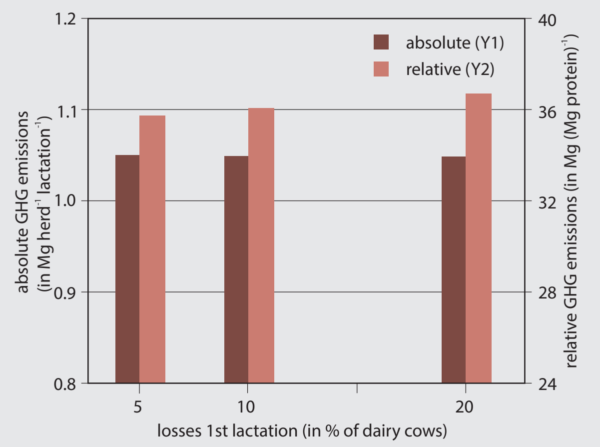

Figure 10

Absolute and protein-related GHG emissions as a function of animal losses (all other variables current as in reference farm)

Figure 11

Absolute and protein-related NH_3 emissions as a function of animal losses (all other variables as in reference farm)

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[8] Between 2004 and 2013, mean milk yields increased at a rate of about 75 kg cow^{-1} a^{-1} (StatBA, 2014), however with considerable differences between the federal states.

Conclusion: Very small changes in absolute emissions can be observed; the effect on protein-related emissions is small, but significant (< 1 %, if losses are halved). Note that reproduction of the herd with high losses is only just possible (see Table 6).

5.2.2 Extended productive lifespan of dairy cows

Extension of the productive lifespan of the dairy cows results in major changes in the overall herd composition. In particular, the number of dairy heifers and the amount of feed they need are reduced. Instead, beef heifers are fattened. All in all, more protein is produced in the herd, which originates from more milk rather than from more meat. The share of meat protein decreases (Table 6).

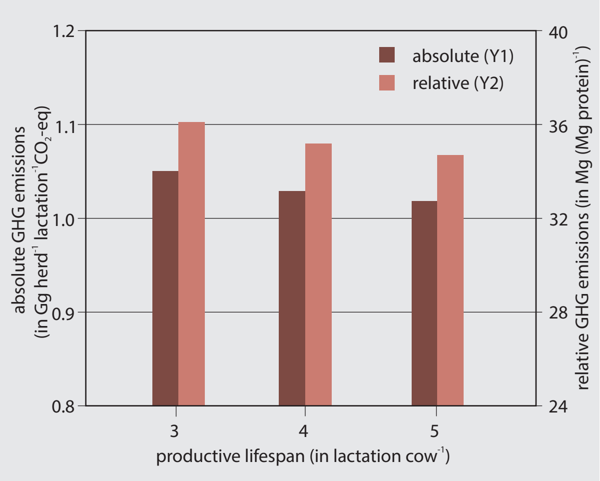

Figure 12
Absolute and protein-related GHG emissions as a function of the useful lifespan of the dairy cows (all other variables as in reference farm)

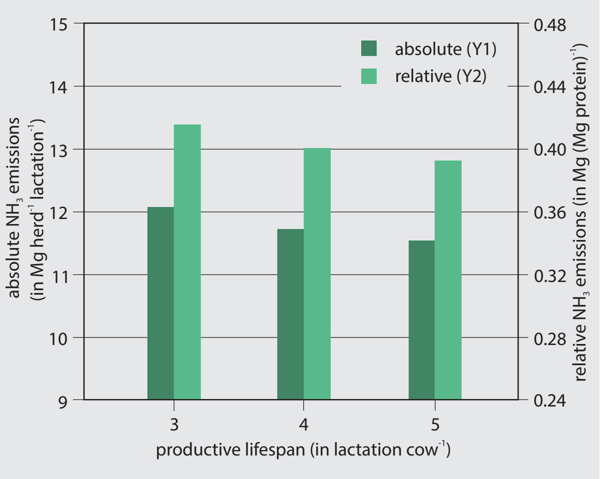

Figure 13
Absolute and protein-related NH_3 emissions as a function of the useful lifespan of the dairy cows (all other variables as in reference farm)

Conclusion: Emissions are reduced by increasing the number of lactations. In principle, this effect becomes smaller with each additional lactation. The shift from 3 to 4 lactations leads to reduced absolute and protein-related emissions (GHG absolute 2 %, relative 2.5 %; NH_3 absolute 3 %; protein-related almost 4 %).

5.3 Effect of grazing

Cattle are herbivores designed for grazing. In principle species-appropriate farming has to include grazing. Furthermore, pastures have long been typical elements of the German cultivated landscape (Brade, 2012). Nevertheless, the share of grasslands has declined in Germany. At present only 42 % of dairy cows have some access to grazing (TopAgrar, 2012). The mean proportion of grazing time in northern Germany is about 0.13 a a^{-1} (Haenel et al., 2016). The major reason for this is the intention to increase milk yields by increased intake of concentrates and reduced overall production costs. How-ever, recent discussions of GHG emission reductions and climate protection, as well as of biodiversity, require a better understanding of the importance of grassland farming and proposals for its expansion (Flessa et al., 2012). In this investigation, all dairy cows and heifers in herds with nominal milk yields of 7000 to 10000 kg cow^{-1} lactation^{-1} are grazed during the vegetation period for 10 h d^{-1}. [9] Dairy heifers are grazed in the second vegetation period of their lifespan. All other cattle are housed exclusively, reflecting the predominant German practice.

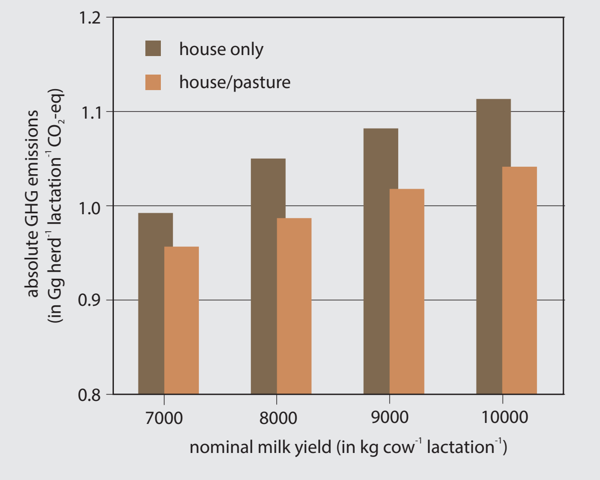

Figure 14
Absolute GHG emissions for the housed herd and for part-time grazing of dairy cows and heifers for varying animal performances (other variables according as in reference farm)

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[9] For grazing and 11000 kg cow^{-1} lactation^{-1} no reliable experimental data are at hand. Therefore, this option is not taken into account.

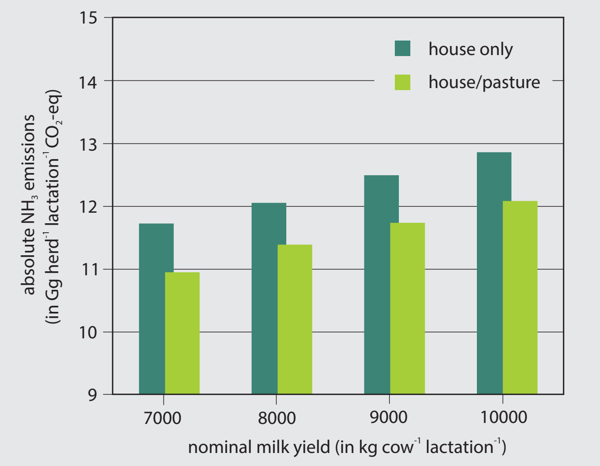

Figure 15

Absolute NH_3 emissions for the housed herd and for part-time grazing of dairy cows and heifers for varying animal performances (other variables as in reference farm)

Conclusion: Figures 14 and 15 illustrate the beneficial results of grazing. For CH_4, the aerobic decay conditions reduce the CH_4 formation from faeces drastically. Urine infiltrates rapidly into the soil and thus reduces the volatilization of NH_3. It has to be kept in mind that calves, bulls and beef heifers are not grazed, and that the grazed animals need extra energy for mobility (and hence more feed). Nevertheless, reductions are very significant at about 9 % for both GHG and NH_3.

5.4 Reduced final weights of beef heifers and bulls

A joint product of milk production is meat production from slaughtered cows as well as from beef bulls and heifers. Dämmgen et al. (2015) showed that higher final weights of beef bulls and heifers result in elevated emissions due to increased energy requirements for maintenance. Lower slaughter weights of beef cattle should have a positive influence on emissions from the entire herd. We therefore took reduced final weights of 435 und 550 kg animal^{-1}, for bulls and heifers, respectively, instead of normal ones (535 und 675 kg animal^{-1}) into account.

Conclusion: 20 % less meat from beef cattle is equivalent to 10 % less meat protein produced by the herd or about 2 % less protein overall. The resulting emission reductions amount to about 5 % for GHG and NH_3 (Figure 16). These figures look promising. However, they contradict present practice where intensive fattening with reduced final weights is not accepted by the markets. Hence, reduced final weights are not considered a realistic emission reduction option.

5.5 Emission reduction by improved fertilizer management

5.5.1 Current practice, modified fertilizing and balance-orientated approaches

Dämmgen et al. (2016), Chapter 2.1, provide a balance-oriented approach for agricultural protein production where the whole production system and the two sub-systems “animal” and “plant/soil” are balanced, i.e. where inputs, outputs and stock changes of nutrients add up to zero.

The N balance for the reference farm (Figure 17) shows that – within the limits of our calculations – the balance can be regarded as closed. Hence reduction measures can only aim at the reduction of losses to emissions and take such improvements into account when the amounts of fertilizers are quantified. This includes renunciation of mineral fertilizers with high losses (urea), improved management practices concerning slurry application and incorporation and increased grazing.

Measures in feed production include the choice of fertilizers (calcium ammonium nitrate instead of urea) as well as the inclusion of N fixation and deposition in calculations. Manure management will have to consider immediate increased use of application techniques that are state of the art and rapid incorporation wherever possible.

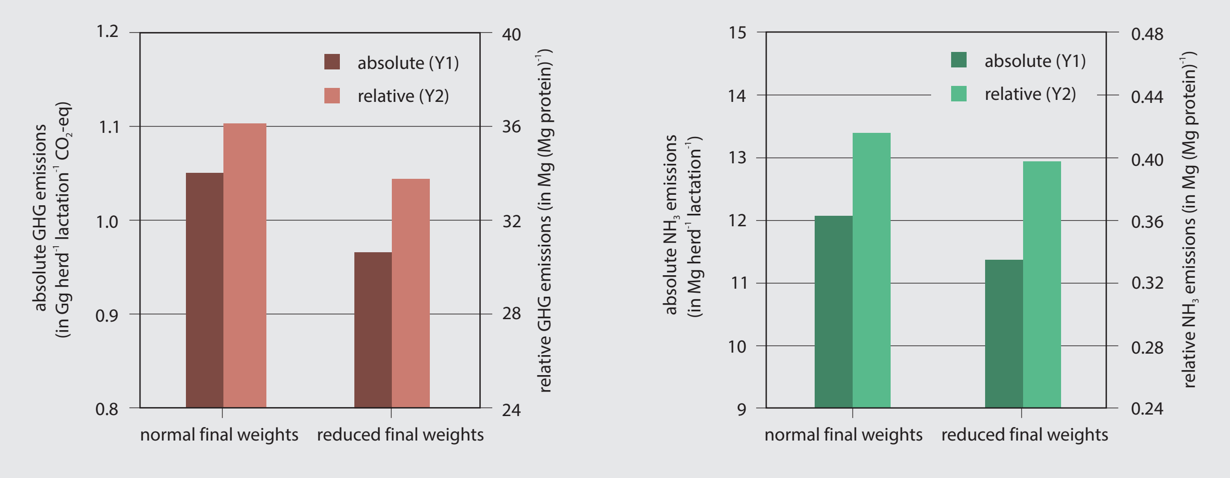

Figure 16

Absolute and protein-related GHG and NH_3 emissions per herd for normal and reduced final live weights (all other variables as in reference farm).

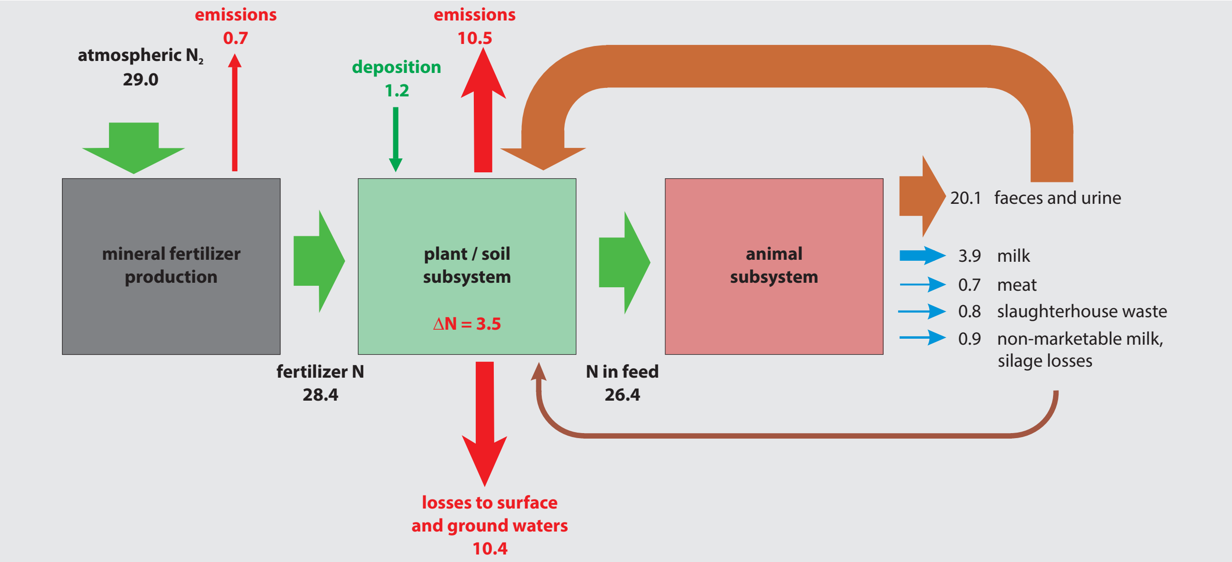

Figure 17
N balance for the reference farm. Fluxes in Mg $herd^{-1}$ $lactation^{-1}$. ΔN in the plant soil subsystem indicates the amount of N that may be stored as additional soil N.

NH_3 emissions from the animal house can only be reduced by adding scrubber systems to a closed building. This is not realistic for cattle houses. Emissions are significantly affected by application techniques and reduced times before incorporation (where possible).

As the rumen biome is very complex and vulnerable (Brade, 2016), it seems at present quite unlikely that enteric fermentation can be reduced by measures applied at the farm level. However, GHG emissions from slurry storage can be reduced in combination with biogas production.

5.5.2 Replacing grass by grass clover mixtures

In grass clover mixtures, the N fixation by the legume contributes significantly to the N budget. For our calculations, we assume a contribution of 50 kg ha^{-1} a^{-1} (LfL, 2013). Fixed N is not considered to lead to direct N_2O emissions (IPCC, 2006). Hence, accounting for N fixation results in reduced mineral fertilizer inputs and hence in reduced direct and indirect emissions from feed production as well as from N fertilizer manufacture.

If 50 % of grass and grass silage are replaced by the corresponding amounts of grass clover mixtures, GHG emissions will be reduced by 2 % and NH_3 emissions by 5 %

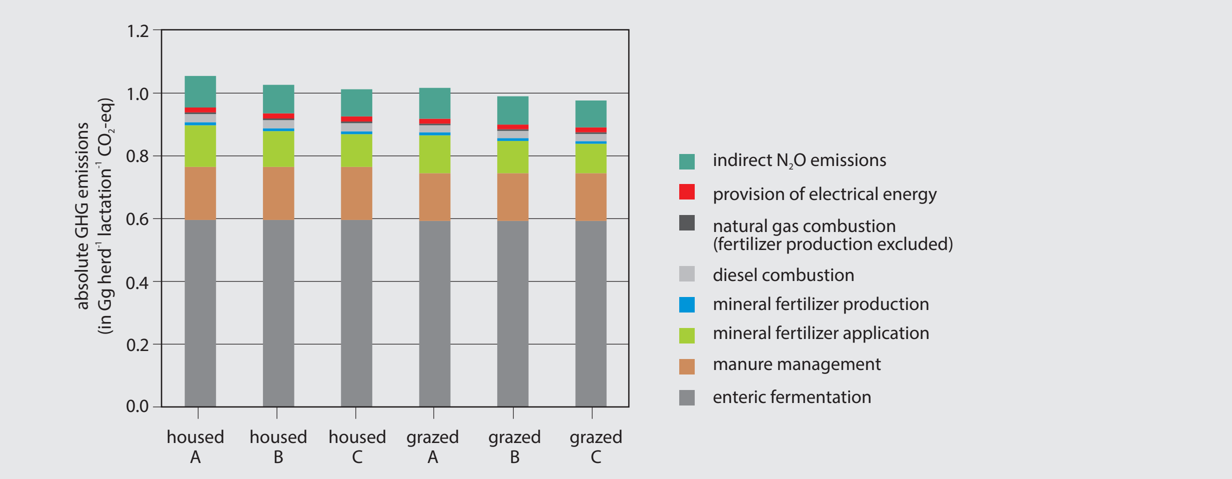

Figure 18
Absolute GHG emissions for reduced mineral fertilizer input (other variables reference values). housed: all animals are housed except dairy heifers (see above): grazed: all dairy cows are grazed part time (8 h d^{-1} during grazing period, 150 d a^{-1}); dairy heifers as above. All other animals kept in house. A: reference situation; B: no solid urea; deposition taken into account; 10 kg ha^{-1} N from N fixation on grassland; C: no urea; deposition and N fixation as in B; surplus covering losses to atmosphere and surface and ground waters reduced to 20 %,

5.5.3 Taking deposition into account

The amounts of atmospheric N deposition (mainly from gaseous NH_3 and NO_2 from NH_4 and NO_3 in particles) are well known in Germany. Even in moderately polluted areas, it may make a contribution to N inputs (at least 10 kg ha^{-1} a^{-1} N, Dämmgen et al., 2013), and this input needs to be taken into account.

We assume an annual N deposition of 15 kg ha^{-1} a^{-1}, of which 10 kg ha^{-1} a^{-1} N are used in our calculations, considering periods without vegetation and losses due to run-off and leaching (for details see Chapter 2.5.7.1 in Dämmgen et al., 2016).

5.5.4 Replacing urea with calcium ammonium nitrate

NH_3 emissions from the application of solid urea (SU) or urea ammonium nitrate solution (UAN) are greater than those of other N fertilizers (emission factor $EF_{\mathrm{NH3,\ SU}}$ = 0.243 kg kg^{-1} NH_3-N, factor $EF_{\mathrm{NH3,\ UAN}}$ = 0.125 kg kg^{-1} NH_3-N; see Dämmgen et al., 2016, Chapter 2.5.8.1). Any replacement with other N fertilizers should lead to reduced NH_3 emissions. Reduced NH_3 emissions will then also result in reduced indirect N_2O emissions. Other side effects are the elimination of CO_2 emissions resulting from the hydrolysis of urea, and of additional liming to compensate for urea's acidifying properties (Dämmgen et al., 2016, Chapter 2.5.9.2).

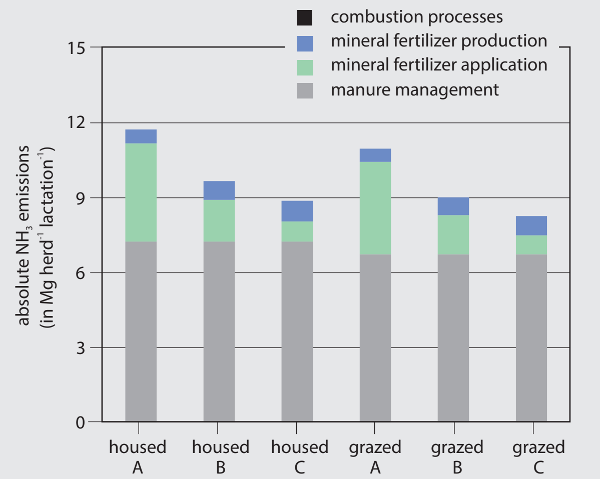

Figure 19
Absolute NH_3 emissions for reduced mineral fertilizer input (other variables reference values) . housed: all animals are housed except dairy heifers (see above): grazed: all dairy cows are grazed part time (8 h d^{-1} during grazing period, 150 d a^{-1}); dairy heifers as above. All other animals kept in house. A: reference situation; B: no solid urea; deposition taken into account; 10 kg ha^{-1} N from N fixation on grassland; C: no urea; deposition and N fixation as in B; surplus covering losses to atmosphere and surface and ground waters reduced to 20 %,

At present in Mecklenburg-Vorpommern, 37.4 % of mineral N is applied as solid urea, another 6.9 % as UAN. In a first step in our calculations, solid urea N is replaced by CAN and UAN, where either replaces half the amount of SU applied. In a second step, all urea-N is replaced by CAN. Replacement of SU reduces the mean emission factor of 0.11 kg kg^{-1} to 0.05 kg kg^{-1}and 0.025 kg kg^{-1}. GHG emissions will be reduced by about 2 %, NH_3 emissions by about 14 % (no solid urea) and 17 % (no urea).

Figures 18 and 19 illustrate the results of combined effects.

Conclusion: It is obvious that the dominant emissions from enteric fermentation and manure management remain unchanged. Similarly, for NH_3 the major contribution of manure management remains constant. In any case grazing reduces emissions.

For GHG, reduction of N inputs with mineral fertilizer slightly affects the direct and indirect N_2O emissions as well as emissions from fertilizer production. NH_3 emissions from fertilizer application are reduced considerably. Changes in the production process result in increased emissions from fertilizer production. NH_3 emissions from combustion processes are negligible.

5.5.5 Improving the manure management system

In all previous chapters, manure management and enteric fermentation were kept constant. Figures 1 and 2 illustrate to what extent CH_4 emissions from manure storage and NH_3 emissions from manure application contribute to the overall emissions. For both GHG and NH_3 these are the major sources of emissions.

5.5.5.1 Slurry application and incorporation

NH_3 emissions during and after slurry application depend on the effective surface area and the time before incorporation on arable land (bare soil). It is still common practice in northern Germany not to use NH_3 abatement techniques to the extent possible.

The reference farm uses a mix of broadcasting and trailing hoses for the application of untreated and biogas slurries, as shown in Table 7. Broad spreading is definitely not state of the art, but still widely used in northern Germany. Variant A is used for all calculations unless stated. Variant B replaces broadcast spreading by trailing hoses and shoes. In Variant C, immediate incorporation using shallow injection is used on bare soil.

The emissions resulting from modified manure application and incorporation are illustrated in Figures 20 and 21.

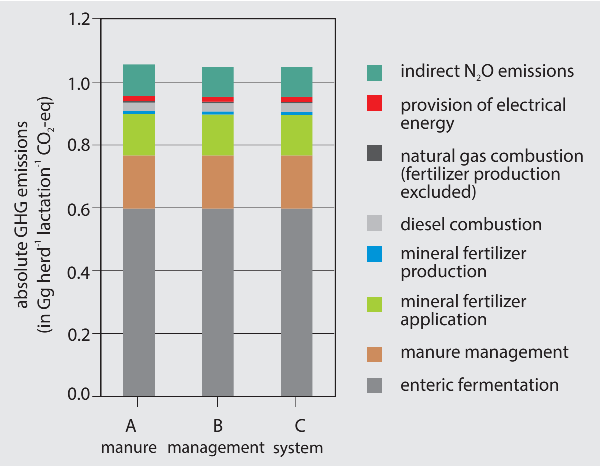

Figure 20

Changes in GHG emissions resulting from modified manure application and incorporation (for variants A, B and C see Table 7)

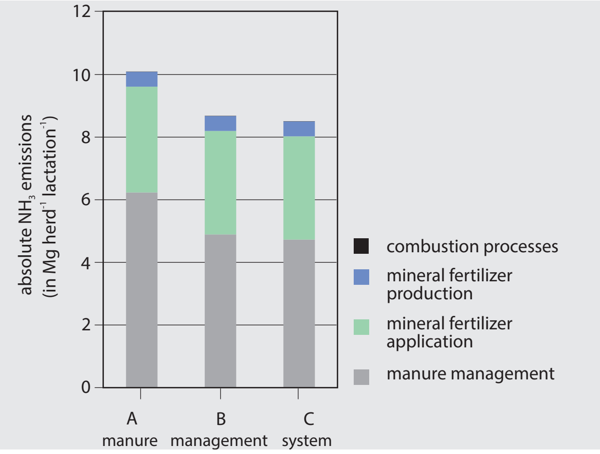

Figure 21

Changes in NH_3 emissions resulting from modified manure application and incorporation (for variants A, B and C see Table 7)

Conclusion: It is clear from Figure 20 that changes in spreading and incorporation have almost no effect on direct GHG emissions (brown bars) and a minor influence on indirect emissions. Decreased emissions are coupled to increased N inputs to soil and hence to small increases in direct N_2O emissions. Differences between A and B and A and C amount to 0.7 %,

In contrast, NH_3 emissions during and after manure spreading can be reduced significantly, if state of the art techniques are applied (Figure 21). Reduced NH_3 losses also lead to reduced N inputs with mineral fertilizer and subsequently to emission reductions during production and application. The effect is small. The advantage of shallow injection as compared to trailing hose and incorporation within 4 hours is small (partial reduction factors compared with broad spreading without incorporation are 0.7 and 0.9 kg kg^{-1}, respectively).

5.5.5.2 Biogas

Biogas production from livestock manures leads to a massive reduction in CH_4 emissions (Figure 22). However, the contribution of enteric CH_4 remains unchanged. Manure management also releases N_2O and the CO_2 from lime in feed.

If biogas is used for direct electricity generation or fed into the national grid, a credit in the national GHG balance takes this into account as this substitutes electric energy produced with fossil fuels (see also Dämmgen et al., 2016, Chapter 2.4.3). The credit for the substitution of fossil energies exceeds the emissions from the generation of electricity.

For the reference herd it is assumed that 20 % of the slurry is treated in a biogas plant. [10] The number of biogas plants is likely to increase, as biogas production and electricity generation have proved economically advantageous in Germany (Fachverband Biogas, 2016).

Table 7

Manure management variants discussed in Chapter 5.6.5.1

variant	spreading and incorporation variants (in % of slurry) A reference situation	 B increased use of hoses	 C increased injection (in addition to B)
arable land			
bare soil, trailing hose, incorporation within 1 h	0	45	20
bare soil, trailing hose, incorporation within 4 h	45	0	0
bare soil, shallow injection	5	5	30
grassland			
broadcast	45	5	0
trailing shoe	5	45	50

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[10] This work does not take into account a potential treatment of the solid manure from calves nor the silage losses in a biogas plant.

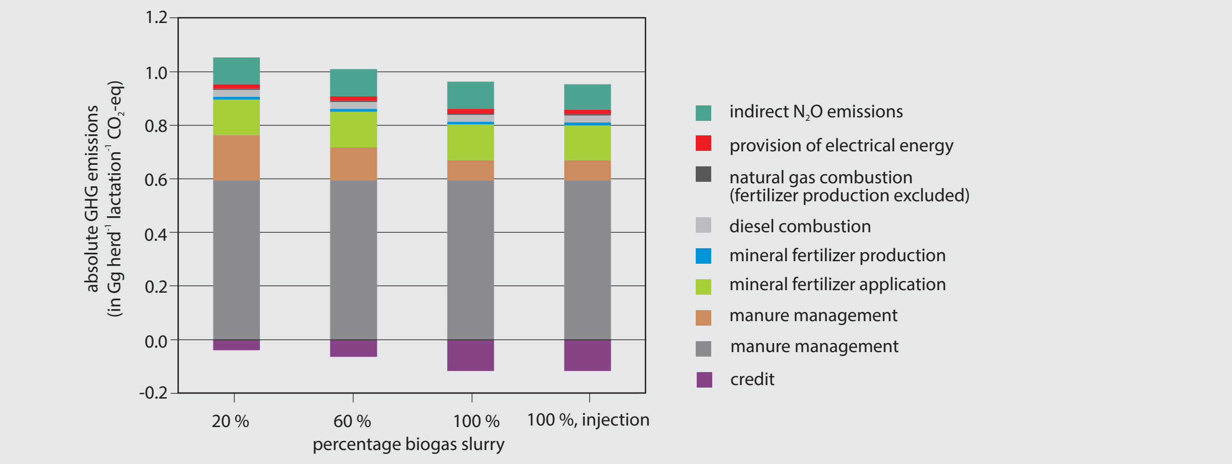

Figure 22
GHG emissions per herd as a function of the share of slurry digested in biogas production (percent of slurry digested; last column using injection on arable land and trailing hose on grassland exclusively, all other variables as reference)

During fermentation, organic N is mineralized to a large extent. In addition, the pH of fermented slurry increases. As a result, NH_3 emissions from the application of biogas slurry exceed those of unfermented slurry (Dämmgen et al., 2016, Chapter 2.4.2). This affects the N balance of the plant production system and the emissions of fertilizer production, as these NH_3 emissions have to be compensated for by increased amounts of mineral fertilizers. Figure 23 illustrates the effect of biogas production on NH_3 emissions. The necessity to combine biogas production with low emission application techniques is obvious.

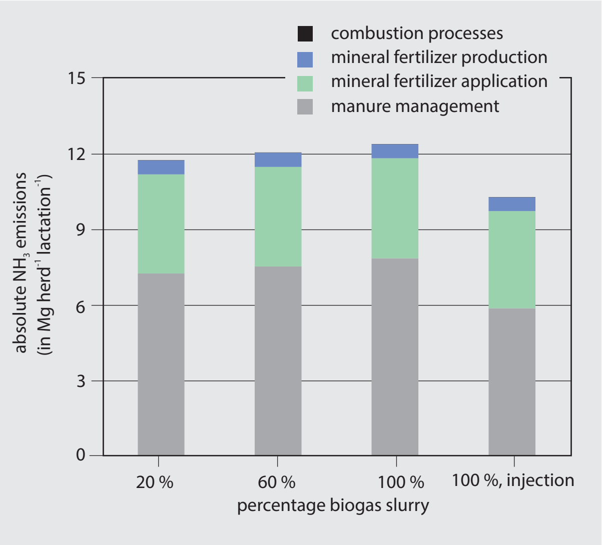

Figure 23
NH_3 emissions per herd as a function of the share of slurry digested in biogas production (percent of slurry digested; last column using injection on arable land and trailing hose on grassland exclusively, all other variables as in reference herd)

Conclusion: For GHG and NH_3, major contributors (enteric CH_4 emissions; NH_3 emissions from the animal house for NH_3) remain unchanged. Biogas production is not only economically useful; it also reduces GHG emissions efficiently. However, it leads to increased NH_3 emissions. Hence it is matter of urgent necessity to use the best application technique possible. However, the reference farm considered here uses 50 % of the slurry to fertilize grasslands where the use of trailing shoes is assumed. The enhanced use of slurry on arable land combined with increased amounts of mineral fertilizers on grassland is likely to further reduce emissions. Careful use of low emission techniques for application and incorporation is necessary in any case.

6 Synthesis and assessment of model results – deduction of recommendations

The overall production system for milk and meat with dairy cow herds is very complex. The primary goal in agriculture is the achievement of profits and the supply of high-quality food. The reduction of emissions or other adverse effects on the environment are goals of the entire society. The conflict of aims is obvious. It is also obvious that this conflict needs to be resolved (Cooper et al., 2013; Heissenhuber et al., 2013). It would not be realistic to expect a short-term reduction in the consumption of milk and beef in Western European societies. The opposite might have to be taken into account (Brade, 2006). Actual projections of agricultural production in Germany assume a steady increase in milk yields of about 100 kg cow^{-1} a^{-1} and a moderate increase in animal numbers (Offermann et al., 2014).

From the results obtained above, we conclude that the following measures for reducing GHG and NH_3 emissions are desirable and feasible:

- Reduction of excess N inputs into the production system (approximate closure of the N balance in plant production)
- Reduction of animal losses and improvement of animal health and welfare.
- Extension of the productive lifespan of dairy cows.
- Greatly improved fertilizer and manure management.
- Increase of biogas production from animal manures (in combination with adequate application techniques for biogas residues).

The obvious pathway to reduced GHG and NH_3 emissions from protein production with dairy cow herds is the intelligent combination of measures. Examples are collated in the scenarios given in Table 8, no longer confined to a single farm, but rather to a region. The results of the respective calculations for these scenarios are presented in Table 9.

Scenario 1 is close to the current practice in northern Germany (see Haenel et al., 2016). Scenarios 2 and 3 assume an annual milk yield increase of 100 kg cow^{-1} lactation^{-1}. In addition, an increase in productive lifespans is taken into account, as is a small increase of the number of dairy cows grazed. It takes into account, that about 10 % of the dairy cows are grazed. A considerable amount of slurry is still broad cast although this is not considered state of the art (arable land: 20 %; grassland 45 %).

Scenario 2 describes the potential situation in 5 years' time, with an increase of 500 kg cow^{-1} lactation^{-1}, the renunciation of solid urea, a minor increase in grazing is assumed, so is an increase in the amount of slurry that is digested.

Scenario 3 aims at an ecologically balanced N budget. The use of solid urea has been discussed for many years. The total renunciation of solid urea presupposes a legal action, so does the application of UAN. Although grass clover mixtures are widely used to produce roughage, the N fixed is not normally accounted for in N budgets. This is also true for the treatment of atmospheric N deposition. The application of low emissions techniques in slurry application has been on the political agenda for at least a decade. However, the assumptions for slurry injection and biogas slurry remain tentative.

Scenario 4 takes into account that milk yields increase as before. The other parameters except the share of slurry digested in biogas plants anticipate minor changes from the current practice. The difference between Scenarios 1 and 4 is to illustrate what political measures and good will can achieve.

The amounts of protein produced in these Scenarios (Figure 24) primarily reflect increased milk yields. Different animal losses explain the difference between Scenarios 3 and 4.

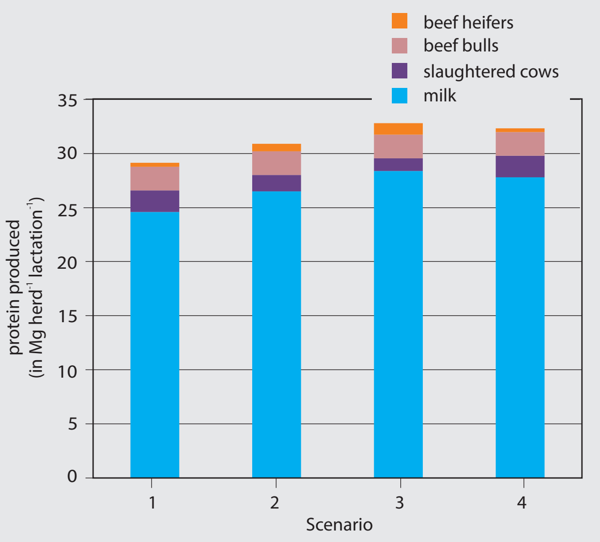

Figure 24
Contributions of animal categories to protein production in Scenarios 1 to 4

Table 8
Scenarios for future reductions of GHG and NH_3 emissions

varied entity	unit	Scenario 1 current practice	Scenario 2 possible in 5 years	Scenario 3 possible in 10 years	Scenario 4 within 10 years, no measures
nominal milk yield	kg cow^{-1} lactation^{-1}	8000	8500	9000	9000
animal losses	% of cows in 1st lactation	10	10	5	10
productive lifespan	lactations cow^{-1}	3	4	5	3
grazing	% of dairy cows *	10	12	14	8
mineral fertilizer	% of DüV recommendations	125 **	125	115	125
solid urea	% of mineral fertilizer mix	37	0	0	37
UAN	% of mineral fertilizer mix	7	adjusted ****	0	7
grass clover	N fixed in kg ha^{-1} N	0	10 *****	20	0
N deposition	kg ha^{-1} a^{-1} N	0	0	10 *****	0
biogas slurry	% of total slurry	20	40	60	40
slurry injection	% of total slurry	5	10	30	5
trailing shoe	% of total slurry	5	20	50	10

* Fraction of dairy cows grazed in a region. Grazing occurs during the whole vegetation period for 8 h d^{-1}. Dairy heifers are grazed in their 2nd summer. For all other animals, grazing is an option not taken into account
** includes the 60 kg ha^{-1} a^{-1} N by which DüV recommendations can be exceeded. A reduction to 40 kg ha^{-1} a^{-1} is anticipated within 10 years
*** AM: animal manures
**** solid urea is replaced by a mixture of UAN and CAN
***** accounted for in N requirement calculations

Scenarios 3 and 4 are the likely boundaries between whom reality might be established. Scenario 3 is by no means a "maximum feasible" option: diet composition may be ad-justed to animal performance; manure application may be improved even for farms without biogas.

The results in Table 9 show the following major relations. Some findings are self-evident:

- Increased milk yields lead to increased absolute excretion rates of VS and N.
- GHG emissions from manure management are strongly depending on the extent of biogas production. However, quantification of the effects of an improved N management is striking. It has long been known that
- Mineral fertilizer application and production decrease when excess fertilization is reduced and when manure N inputs are adequately accounted for. This results in reduced NH_3. It also reduces total GHG emissions, in particular direct and indirect N_2O emissions.
- NH_3 emissions are governed by emissions from livestock buildings and slurry application. Whereas the emissions from houses can be affected by feed composition and grazing time, the effect of reduced inputs of mineral fertilizers can be clearly seen. The extent to which NH_3 emissions reductions are possible exceeds the relative reduction potential of GHG emissions by far.
- Increased performances require larger areas for feed production. The difference between Scenarios 3 and 4 indicates that grazing may help to reduce this effect.
- Differences between these results are even more significant if one relates emissions to the amounts of protein produced.
- N balance and N efficiency can be improved considerably.

For each single measure, the effects are considered small. It can be shown that they add up considerably when combined, as can be seen from Table 9.

Despite increased milk production, enteric CH_4 emissions decrease from Scenario 1 to Scenario 3. However, the difference between Scenarios 3 and 4 is just 4 %. The effect of improved management is by far more important. 11 % can

Table 9

Excretions and emissions of a dairy herd with 100 cows and their offspring resulting from the assumptions made in Table 8

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Excretions					
CH_4 enteric	Mg herd^{-1} lactation^{-1} CH_4	23.8	23.5	23.4	24.4
VS	Mg herd^{-1} lactation^{-1} VS	383	399	418	391
N	Mg herd^{-1} lactation^{-1} N	20.2	20.3	20.9	21.5
GHG emissions	Gg herd^{-1} lactation^{-1} CO_2-eq				
enteric fermentation		0.595	0.588	0.586	0.610
manure management		0.112	0.095	0.070	0.092
MF application *		0.132	0.117	0.096	0.135
MF production		0.010	0.009	0.008	0.010
combustion processes		0.026	0.026	0.026	0.027
provision of electrical energy		0.016	0.018	0.020	0.017
N_2O indirect		0.101	0.048	0.082	0.104
total GHG		1.053	0.962	0.951	1.060
GHG credit		0.010	0.030	0.065	0.036
NH_3 emissions	Mg herd^{-1} lactation^{-1} NH_3				
manure management		7.92	7.85	6.31	8.02
MF application		3.96	1.76	0.74	4.03
MF production		0.56	0.79	0.75	0.57
total NH_3		12.44	10.40	7.80	12.62
cultivated area	ha herd^{-1}	118.4	117.9	115.7	120.9
protein-related emissions					
GHG	Mg (Mg protein)$^{-1}$ CO_2-eq	36.4	31.3	29.0	32.1
NH_3	Mg (Mg protein)$^{-1}$ NH_3	0.428	0.337	0.308	0.401
N balance **	kg ha^{-1} lactation^{-1} N	196	188	179	189
N efficiency ***	kg kg^{-1}	0.167	0.183	0.194	0.177

* MF: mineral fertilizer

** see Dämmgen et al. (2016), Chapter 2.11.1;

*** see Dämmgen et al. (2016), Chapter 2.11.2.

be achieved for GHG from manure management, and more than 30 % from mineral fertilizer application and production. The overall reduction between careful farming (Scenario 3) and business as usual exceeds 10 % (absolute) and a similar percentage, if GHG emissions are related to the amounts of protein produced.

The GHG credit is small in comparison with the absolute figures. However, it adds another 7 % to the potential reduction (Scenarios 3 and 4) – a welcome side effect.

The comparison between Scenarios 3 and 4 reveals that a reduction of NH_3 emissions of more than 50 % may be possible (as a combination of feasible steps). Again, the improved manure management and the reduced N input into the system result in considerable potential emission reductions. This affects indirect N_2O emissions significantly.

All in all, it could be shown that measures improving animal health and welfare and management improvements cause desirable emission reductions at no additional costs. However, these findings also confirm that the emission reduction goals (reduction to 71 % of 2005 by 2030, EU, 2016), presuppose a reduction of animal numbers (if our findings can be extrapolated to other fields of animal production).

7 Discussion

7.1 Uncertainties

The uncertainties of input parameters are discussed *in extenso* in Dämmgen et al., (2016). However, it should be repeated that the uncertainties of relative changes are smaller than those assumed for the absolute entities.

7.2 Comparative data

Nijdam et al. (2012) collated results of ***life cycle analyses.*** They show a wide range of results for milk and beef production (treated separately). The 52 approaches described differ considerably, in particular for the treatment of joined products, but also with respect to their input parameters (production intensity, feed used, farming system, manure and mineral fertilizer managements, infrastructure, means of transport and processes subsequent to farming). On the whole, however, the results do not contradict the findings of this paper.

Our findings for milk-related GHG emissions [11] presented in Table 10 illustrate to what extent product-related GHG emissions vary with performance and management. Increased milk yield (comparison of 7000 and 11000 kg cow^{-1} lactation^{-1}) more than halves the product related emissions. Improved management also almost halves these emissions (comparison of Scenarios 3 and 4).

GHG emissions per kg of milk obtained with our calculations for a nominal milk yield of 8000 kg cow^{-1} lactation^{-1} (reference conditions) amount to 0.87 kg (kg milk)$^{-1}$ CO_2-eq. Analysis of further published data reveals the amount of scatter. However, recently published data (Flysjö et al., 2012; 0.8 to 1.0 kg (kg milk)$^{-1}$ CO_2-eq); Thoma et al., 2013; Vergé et al., 2013) are in the same order of magnitude. In western provinces of Canada 0.93 kg (kg milk)$^{-1}$ CO_2-eq, in eastern provinces with considerably smaller herds 1.12 kg (kg milk)$^{-1}$ CO_2-eq were reported. They also agree with Reinhard et al. (2009) who calculated about 0.8 kg (kg milk)$^{-1}$ CO_2-eq for agricultural feed production and enteric fermentation. O'Brien et al. (2014) investigated the Irish grass-based system and found 0.837 kg (kg milk)$^{-1}$ CO_2-eq for a milk yield of 6696 kg cow^{-1} a^{-1} ECM [12]; they also reported UK data of 0.884 kg (kg milk)$^{-1}$ for housed animals and 10600 kg cow^{-1} a^{-1} ECM. For the average British farm with 7490 kg cow^{-1} a^{-1} milk a footprint of 1.3 kg (kg milk)$^{-1}$ CO_2-eq was determined (DairyCo, 2012). Müller-Lindenlauf et al. (2014) published GHG emissions for milk. For German farms in 2010 with slightly different system boundaries, mean GHG emissions of about 1.1 kg kg^{-1} CO_2-eq were deduced for the production of 1 kg milk. However, that paper used simplifying calculation procedures which are not valent to ours and did not include animal performance as a

Table 10
GHG emissions attributed to milk production, related to nominal milk yields (in kg (kg milk)$^{-1}$ CO_2-eq). Apart from milk yield and housing / grazing, all parameters are used as in Table 8.

nominal milk yield	nominal milk yield (in kg cow^{-1} lactation^{-1})								
	7000		8000		9000		10000		11000
housed / grazed	h	h / g	h	h / g	h	h / g	h	h / g	h
conditions as in Scenario									
1	0.952	0.928	0.866	0.846	0.804	0.782	0.749	0.726	0.698
2	0.899	0.879	0.818	0.802	0.760	0.742	0.709	0.688	0.660
3	0.863	0.845	0.786	0.771	0.720	0.706	0.682	0.663	0.636
4	0.923	0.901	0.840	0.822	0.778	0.760	0.727	0.705	0.677

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[11] GHG emissions were allocated to milk production using the approach described in Dämmgen et al. (2016), Chapter 2.11.3. They relate GHG to marketable milk produced..

[12] ECM: energy corrected milk

variable. Allocations were based on economic data rather than energies.

A directly comparable treatment of ***N flows and NH_3*** emissions from protein production with dairy herds is hitherto unknown.

NH_3 footprints for milk use emission data per cow as provided by Eurostat (e.g. Danish Agriculture & Food Council, 2015). These do not include the emissions of the "other cattle" in the herd producing dairy cows (i.e. half the calves and all dairy heifers), nor do they include the respective emissions from mineral fertilizer application in feed production or the emissions from the production of these fertilizers.

N inputs with manures and mineral fertilizers and N balance of our practice-orientated Scenarios 1 and 4 agree with values published in Osterburg (2007) and calculated from representative German book-keeping farms for the year 2000. However, it should be noted that the balancing procedure of OECD does not take emissions and leaching into account. Both can be reduced but cannot be avoided in principle.

7.3 Relevance and potential translation into practical action

Numerous studies have dealt with variations of single input parameters on emissions from milk or beef production (e.g. O'Mara, 2004; Garnsworthy, 2004; Tamminga et al., 2007; Flachowsky and Hachenberg, 2009; Taube and Herrmann, 2009; Walter, 2009; Bell et al., 2011; Niemann et al., 2011; Zehetmeier et al., 2012).

This paper also analyses and assesses single production factors, which are then combined to quantify combined effects on the production of edible protein.

Readers will have noticed that ***manipulations of the rumen biome*** in order to modify enteric fermentation were not taken into account. Intentional modifications of the rumen biome – largely a black box (Morgavi et al., 2010; Kim, 2012) – are not within the farmers' present scope of action. Also, the potential use of ***hormones***, such as BST, was not considered for similar reasons. ***Genetically modified feeds*** do not need extra treatment in an analysis such as this one, as their influence is dependent on their constituents in the same way as conventional feed.

In contrast, ***increasing performance*** of dairy and beef cattle is not only possible but common practice. [13] As a rule, increased ratios of concentrates to roughage (reduction of overall fibre contents) result in reduced CH_4 emissions from enteric fermentation per unit of product (e.g. Brade et al., 2013, or Dämmgen et al., 2015).

Changes in ***size of dairy cattle*** were not considered in our model calculations. However, it is clear that bigger and heavier animals require more maintenance energy and excrete more VS and N. Hence, lighter animals should be strived for. Smaller animals also produce more milk during their entire lifetime (extended productive lifespan, see below) (Simon, 2010; Brade, 2017).

Data on ***animal losses*** and welfare are sparse, even more so relations between animal performance and disease incidence (cf. Dämmgen et al., 2016). Recent data sets were available for Mecklenburg-Vorpommern, indicating high incidences and losses (Rudolphi et al, 2012). Prien (2006) and Hellerich (2008) published data for Schleswig-Holstein indicating lower incidences and loss rates than Rudolphi et al. (2012): Prien (2006) found incidences of about 64 % and premature losses of cows of about 31 %, and Rudolphi et al. (2012) mentioned incidences of 77 %. Highest losses were reported for young cows indicating different coping with the effects of negative energy balances after calving (Brade et al., 2008). By and large, ***the assumption of reduced animal losses is realistic. Improved animal health is feasible.***

The extension of the ***productive lifespan*** is closely connected to animal losses. Missfeldt et al. (2015) made clear that a reduction of losses due to premature slaughtering or perishing by 10 % will increase the number of lactations per cow from the present 2.6 to 3.4 to 3.7. Halving the losses would extend the productive lifespan to 5.2 lactations. It has long been known that milk yield peaks with the fifth lactation (Brade, 2006). This is in line with the statement that more than nine lactations are economically optimal (Missfeldt et al., 2015). On the contrary, farms with long productive life spans do without the "normal" increase in productivity of about 75 kg cow^{-1} $lactation^{-1}$ milk. The present German situation with 2.6 lactations per cow does not allow for any selection as all female animals will be needed to preserve the herd. ***An extension of the productive life of dairy cows is not only a matter of animal welfare and economy, it is highly necessary for reasons of (eventual) culling and selection.***

The production of healthy and highly productive dairy cows can be best achieved with young female animals, which also graze during part of the rearing period (DLG, 2008; Elsässer et al., 2014). Grazing dairy heifers at least part of their lives is still standard (Dämmgen et al., 2015). However, part-time grazing of dairy cows has had a negative trend in the past. The small changes in Scenarios 2 and 3 are optimistic; business management and stable milk yields, automation of milking and more efficient feeding are likely reasons (Brade, 2012). However, "Weidemilch" (milk from grazed animals) is now common in German supermarkets, indicating changed consumer attitudes (dairies pay a higher price to the farmer; consumers accept the supply on the shelf). Last but not least the necessity to reduce emissions will have to cause new reflections on grazing. ***There are good reasons for increased grazing. This would reduce emissions in general.*** However, more and more, grasslands and pastures have to be managed under conditions of nature conservation, which affects the use of fertilizers, pest control measures and quality maintenance. Grasslands without the necessary feed properties and amounts cannot be used in intensive animal production. However, these considerations are beyond the scope of this paper.

As could be shown above, manure management has a decisive effect on emissions. Economic reasons favour the

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[13] Increase in performance is not just "happening", it is "programmed" as shown by the present trends in Holstein breeding programmes (Brade et al., 2013; Brade and Brade, 2014)

investment of capital into biogas plants, which is positive from the point of view of GHG emission reduction. It is quite clear that it has to be combined with highly efficient methods of biogas slurry application techniques to reduce the adverse effects on NH_3 emissions. ***A moderate increase of the number of biogas plants must be anticipated, also of the use of low emission application techniques. It is unclear whether the latter increase at the same speed as biogas plants.***

Current plant production makes use of a quantification of mineral fertilizers using the respective data provided in the fertilizer enactment. Here, the calculation procedure has to be improved; an ecologically sound mineral fertilizer equivalent of manure N has to be used in parallel with a reduction of the allowed surplus. In addition, the current practice of manure application and incorporation have to be improved using the tools and knowledge available. Such steps towards an environmentally and climate friendly agriculture also result in a reduction of the currently observed nutrient surplus. ***A more balance-orientated calculation procedure treating manure N more realistically in combination with measures to increase N use efficiency along the entire production chain reduces both GHG and NH_3 emissions drastically.***

The present figures for **N balances** and **N efficiency** (bottom of Figure 9) show a large potential to improve resource efficiency and N productivity in agriculture, and continuing with current N balance is alarming for reasons of environmental pollution and climate protection.

The increase of N use efficiency and the reduction of surplus in agriculture is a must.

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Appendix

Table A1

Example GHG emissions of the reference herd, complete list for animals kept in the house at all times and for part-time grazing of dairy cows and dairy heifers, ranking according to GHG emissions

		emissions			
		in Mg herd^{-1} lactation^{-1}		in Gg herd^{-1} lactation^{-1} CO_2-eq	
source	gas	housed	housed / grazed	housed	housed / grazed
enteric fermentation	CH_4	23.82	23.71	0.595	0.593
manure management	CH_4	4.70	4.23	0.117	0.106
mineral fertilizer application	N_2O	0.28	0.27	0.083	0.080
manure management	N_2O	0.17	0.15	0.050	0.044
indirect emissions from leaching	N_2O	0.16	0.17	0.048	0.049
indirect emissions from depositions	N_2O	0.17	0.16	0.052	0.049
liming	CO_2	31.49	24.22	0.031	0.024
combustion of diesel	CO_2	23.55	20.26	0.024	0.020
provision of electrical energy	GHG	15.75	15.34	0.016	0.016
mineral fertilizer production, lime quarrying	GHG	0.010	0.009	0.010	0.009
urea application	CO_2	17.82	17.11	0.018	0.017
combustion of natural gas (except mineral fertilizer production)	CO_2	4.88	4.96	0.0049	0.0050
silage losses in manure management	CH_4	0.162	0.121	0.0041	0.0030
combustion of diesel	N_2O	0.009	0.008	0.0027	0.0023
lime in feed	CO_2	1.370	1.394	0.0014	0.0014
grazing (excreta)	CH_4	0.000	0.059	0.0000	0.0015
silage losses in manure management	N_2O	0.006	0.004	0.0018	0.0013
non-marketable milk in manure management	CH_4	0.014	0.013	0.0003	0.0003
combustion of natural gas (except mineral fertilizer production)	N_2O	0.001	0.001	0.0003	0.0003
non-marketable milk in manure management	N_2O	0.0003	0.0003	0.0001	0.0001
combustion of natural gas (except mineral fertilizer production)	CH_4	0.0009	0.0009	0.0000	0.0000

Table A2

Example NH_3 emissions of the reference herd, complete list for animals kept in the house at all times (except dairy heifers) and for part-time grazing of dairy cows and dairy heifers

	emissions in Mg herd^{-1} lactation^{-1}	
source	housed	housed / grazed
manure management, application	4.03	3.63
mineral fertilizer application	3.94	3.79
manure management, house	2.87	2.60
manure management, storage	0.57	0.51
mineral fertilizer production	0.56	0.54
grazing (excreta)	0.00	0.22
silage losses in manure management	0.14	0.10
non-marketable milk in manure management	0.01	0.01