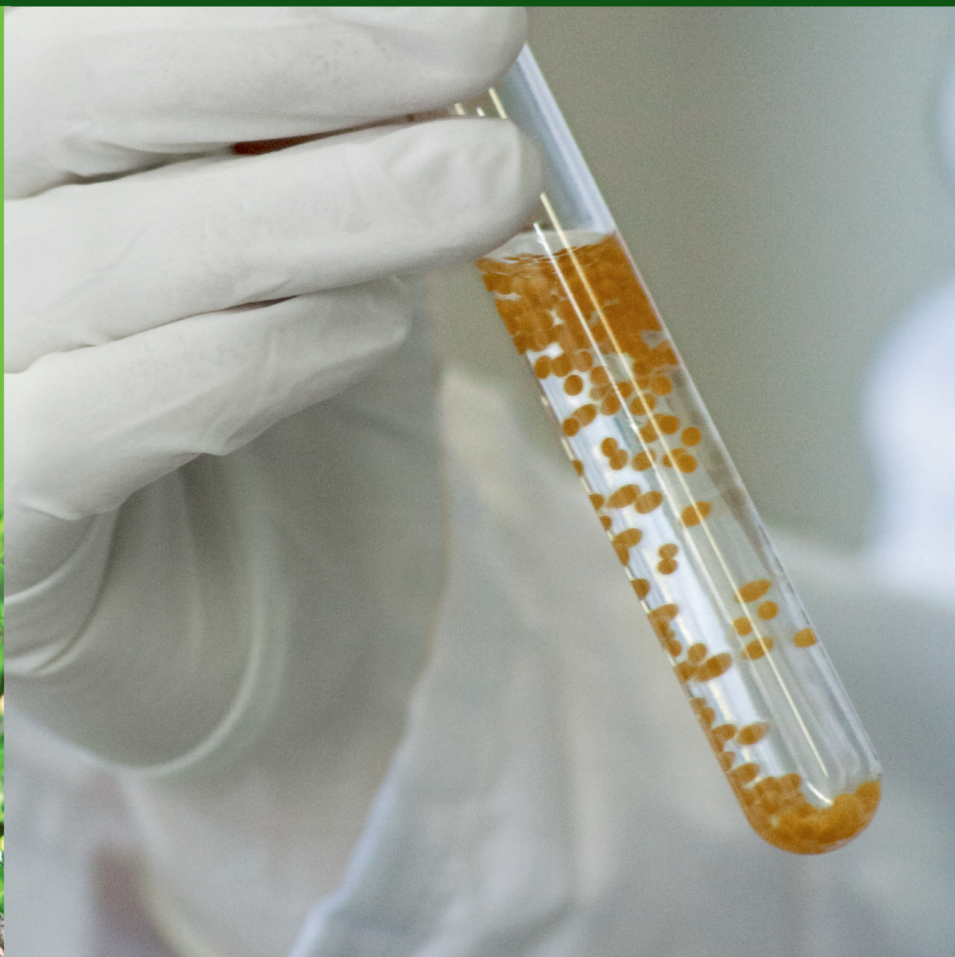
Landbauforschung

Applied Agricultural and Forestry Research

Vol. 66
No. 3 · 09.2016



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Indexiert in: CAB International, Science Citation Index Expanded, Current Contents – Agriculture, Biology & Environmental Sciences, Scopus, Web of Science.

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ISSN 0458-6859

Gedruckt auf FSC-zertifiziertem Papier

Applied Agricultural and Forestry Research

Landbauforschung *Applied Agricultural and Forestry Research* is a scientific journal, concerning the latest research results of socially relevant issues related to agriculture, forestry and rural development. The journal is targeted explicitly to interdisciplinary topics.

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The print edition is published quarterly. Articles not yet assigned to a specific issue are available online (“Online First”)

Indexed in: CAB International, Science Citation Index Expanded, Current Contents – Agriculture, Biology & Environmental Sciences, Scopus, Web of Science.

Publisher
Johann Heinrich von Thünen Institute

Editor in Chief
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Graphic Design and Typesetting
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Photos cover pages
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ISSN 0458-6859

Printed on FSC-certified paper

Landbauforschung
Applied Agricultural and Forestry Research
Vol. 66 No. 3 09.2016

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DOI:10.3220/LBF1480076778000

Gaseous emissions arising from protein production with German Holsteins – an analysis of the energy and mass flows of the entire production chain 1. Goals, methods and input data

Ulrich Dämmgen*, Wilfried Brade**, Ulrich Meyer***, Hans-Dieter Haenel*, Claus Rösemann*, Heinz Flessa*, Jim Webb****, Michael Strogies*****, and Manfred Schwerin******

Abstract

This work describes the methods used for the calculation of gaseous emissions from protein production using a mass flow analysis of cattle herds of highly productive German Holsteins and the relevant energy requirements. This includes cows, the animals required for reproduction as well as female and male beef cattle. Both milk and beef production are considered. Those parameters which can be modified by the farmer receive special attention: such as grazing versus housing; performance and productive life span of the cows; diseases and livestock losses in the entire herd; manure management. In addition, the respective plant production (including fertilizing, conservation and the respective losses, biogas production) is dealt with. Emissions from fertilizer production and emissions from feed processing are considered, as are emissions from the provision of water, natural gas, diesel and electricity.

The complex model allows for the identification, quantification and valuation of potential emission reductions (effects and side effects) for the production of edible protein. As far as possible, our approach prefers scaled data and avoids the use of default values. The same input data are used to calculate emissions of greenhouse gases and reactive nitrogen species. Emissions arising from the erection and maintenance of buildings, production plant and machinery, the production and application of pesticides, feed additives, veterinary medicine as well as storage and transport of feeds are not included. The work avoids the use of imported feeds.

The results are communicated in companion papers (Dämmgen et al., 2016 a, b).

Keywords: *cattle herd, emissions, greenhouse gases, ammonia, mass flow analysis*

Zusammenfassung

Gasförmige Emissionen bei der Eiweißerzeugung mit Deutschen Holsteins – eine Analyse der Energie- und Stoffflüsse der gesamten Produktionskette 1. Ziele, Methoden und Eingangsdaten

Vorliegende Arbeit beschreibt die Methoden zur Erfassung der Stoffströme und der sie treibenden Energieströme in kompletten Rinderherden bei der intensiven Milch- und Rindfleischerzeugung mit Deutschen Holsteins bei variierter Haltung, Leistung und Nutzungsdauer der Milchkühe sowie Krankheiten und Verlusten in der Herde. Abgebildet werden Wirtschaftsdüngermanagement, die vorgelagerte pflanzliche Erzeugung sowie die Emissionen aus der Düngerproduktion, der Futtermittelverarbeitung und der Bereitstellung von Wasser, Erdgas, Diesel und elektrischer Energie.

Diese Methoden erlauben das Erkennen und Bewerten von Emissionsminderungspotentialen in der Erzeugung von essbarem Protein mit Rinderherden. Die Emissionen von Treibhausgasen (THG) und von stickstoffhaltigen Gasen werden aus den gleichen Datensätzen berechnet. Nicht betrachtet werden Emissionen aus der Erstellung und Erhaltung von Gebäuden, Produktionsanlagen und Maschinen, aus der Anwendung und Produktion von Pflanzenschutzmitteln, Futtermittelzusatzstoffen oder Tierarzneimitteln und aus Lagerung und Transport von Futtermitteln. Der Einsatz importierter Futtermittel wird vermieden.

In weiteren Arbeiten (Dämmgen et al., 2016 a, b) werden zugehörige Ergebnisse mitgeteilt.

Schlüsselwörter: *Rinderherde, Emissionen, Treibhausgase, Ammoniak, Stoffflussanalyse*

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1 Introduction

Climate change and its adverse effects call for reductions of the emissions of those gases that cause changes in the atmosphere's energy balance. Such a reduction is likely to change agricultural production processes. Emission reduction therefore has to look at livestock production in the first place, and identify and quantify reduction potentials. The pathways which produce greenhouse gases (GHG), in particular methane (CH_4), are closely interlinked with those of nitrogen (N) and the emissions of N species such as ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O) and di-nitrogen (N_2). Of these, NH_3 is of special importance as air pollutant. In 2013, Germany's agricultural livestock and crop production contributed 6.7 % to national of GHG emissions. If fertilizer production, energy and water consumption are taken into account, 15 % of national GHG emissions can be attributed to agriculture. In 2013 agriculture's share of NH_3 emissions was 94.4 % of the national total (UBA, 2015 b). About half of the agricultural emissions originate from cattle herds. Milk and beef production systems therefore have priority in emission reduction research. At present, climate change targets have yet to be agreed on, while for NH_3, EU legislation aims at a reduction to 95 % of the 2005 emissions. The long-term goal is a reduction to 71 % of 2005 by 2030 (EU, 2016).

In a society where protein consumption is well above nutritional requirements (DGE, 2012), a reduction of animal numbers might be a wise decision. However, Germany expects additional exports, resulting in increased animal numbers and higher animal performance, in particular higher milk yields per cow (Offermann et al., 2014). Hence measures to use nutrient and energy fluxes more efficiently have to be identified. Any unnecessary inputs into the system are to be avoided. For cattle, grazing, even for high performance dairy cows, might be an option for emission reduction. The preservation of grasslands or even their extension is considered (carbon preservation). In a densely populated country land utilization and landscape aspects are topics to be considered. On the other hand, the society asks for high-quality food at moderate prices, and farmers need to generate an adequate income.

Any compromise has to include complex treatments of the agricultural production system; mono-causal approaches are insufficient and may even lead to false estimation and valuation of emission reduction measures. Therefore, a comprehensive mass flow analysis as recommended by OECD (2008) for the cattle herd with milk and meat as their joined products is aimed at in this paper. The findings of other authors dealing with these sectors has been taken into account including reviews (e.g. Flachowsky et al., 2011; Havlik et al., 2014) or papers dealing with performance and breeds (Zehetmeier et al., 2011; Bell et al., 2013), feed and feed additives (Kirchgeßner et al.,1993; Johnson et al., 2002; van Zijderveld et al., 2011), housing and grazing (Jiao et al., 2014; Rotz et al., 2010; Yan et al, 2013; O' Brien et al., 2014) or dairy farm economics (van Middelaar et al., 2014).

This paper deals primarily with those parameters which can be modified in agricultural production systems by persons responsible, such as:

- animal performance (dairy cows: milk yield; beef cattle: growth)
- housing and grazing
- productive lifespan, animal health and welfare
- feed production (including use of mineral fertilizers)

Parameters which are not within this scope, such as soil properties, amounts and composition of precipitation, are considered constant.

In order to reduce the number of input data, we confine our reflections to Holstein herds in Northern Germany. For this region (Schleswig-Holstein, Niedersachsen, Mecklenburg-Vorpommern, Brandenburg, Nordrhein-Westfalen), data sets are available for numerous input parameters which makes the use of default values unnecessary (which are often incompatible).

The paper at hand is restricted to the description of methods and input data. Results are presented in Dämmgen et al. (2016a; b).

2 Materials and methods

2.1 Margins of balancing

The goal of this work is the quantification of emissions from processes governing protein production by dairy cow herds. This ***includes:***

- emissions from animal metabolism (CH_4) and from manure management (CH_4 as well as NH_3, NO and N_2O,
- NH_3, NO, N_2O and N_2 emissions from the plant soil system during feed production,
- carbon dioxide (CO_2), CH_4 and N_2O emissions from the combustion of diesel fuel and GHG emissions from CH_4 combustion,
- GHG, NH_3 and particulate ammonium N (NH_4-N) emissions from fertilizer production,
- GHG emissions from processing of feeds (silage production, processes in grain and oil mills as well as sugar beet factories including electrical energy),
- emissions from the provision of water and fuels.

It does ***not include***

- emissions from the construction and maintenance of buildings and production plants or machinery,
- emissions from the application and production of active substances (e.g. pesticides), feed additives (e.g., silage inoculants) or veterinary drugs,
- emissions originating from storage of feeds or from transport processes within and outside the farm,
- emissions from human metabolism,
- potential carbon sequestration.

CO_2 released from animal metabolism and manure management is not considered an emission. This is because the CO_2 emitted by the respiration of crops and livestock will have been fixed during photosynthesis.

The margins of balancing N flows are illustrated in Figure 1. Mass balances can be carried out for the entire system "herd" and its two sub-systems "plant/soil" and "animals". In principle, the total of the respective inputs, outputs and changes in pools adds up to zero when the systems are in a steady state. Processes outside these systems but taken into account are fertilizer production, cereal and oil mills and sugar beet factories.

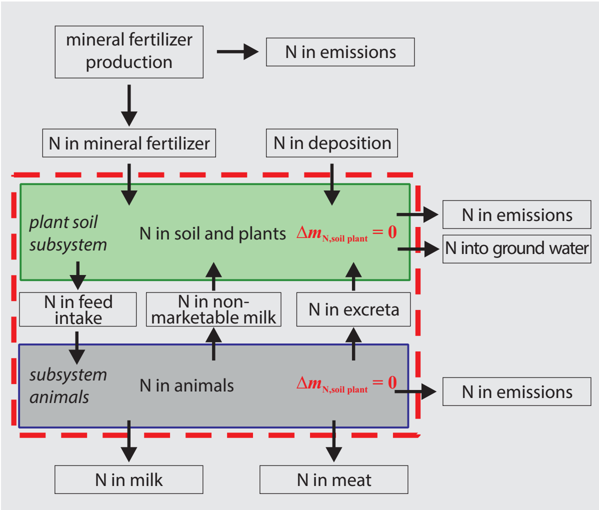

Figure 1
N flows in the system "herd" (red broken frame) und the sub-systems "plant soil" and "animals"

Table 1
Example animal losses in dairy herds

	overall losses (slaughtered and perished animals) x_{loss} animal animal^{-1}	share of utilized animals (slaughtered animals) ****** x_{util} animal animal^{-1}
dairy cows, 1st lactation	0.20 *	0.92
dairy cows, subsequent lactations	0.07	0.92
calves (total)	0.15 **	0.0
female calves	0.12 ***	0.0
male calves	0.18 ***	0.0
dairy heifers	0.01 ****	0.6
beef heifers	0.03	0.6
beef bulls	0.06 *****	0.6

* see text above
** Fischer (2007); Rudolphi et al. (2012);
*** e.g. Kargo et al. (2014);
**** Harms (undated, a);
***** NIBIS (2013); Arbeitsgruppe BZA Bullenmast (2015).
****** expert judgement W. Brade reflecting literature data for dairy cows, bulls and heifers. "Normal" illnesses affecting elder animals such as infertility, injuries of the claws or weakness of limbs do not affect the carcass quality. Typical diseases of calves are diarrhoea, pneumonia, emaciation and asthenia. Carcasses of calves are of little use for meat production, and as a rule disposed of.

2.2 The herd

2.2.1 Animal numbers and losses

A differentiation is necessary between animals that have to be fed, and the number of those born or utilized. Also, animal losses have to be considered (Table 1) [1]. The unit of time in our investigation is "lactation"[2].

The number of dairy cows in the herd is kept constant (steady state). Animals taken out are slaughtered (utilized animals) or perish. In Northern Germany, high losses during the first lactation have been observed (Table 1 and Appendix 1) (Fleischer et al., 2001; Krömker and Pfannenschmidt, 2005; Fischer, 2007; Brade et al., 2008; Rudolphi et al., 2012; Harms undated, b). Schwerin (2009) traces many of them back to problems related to coping with the negative energy balance after calving.

The term "entire herd" is used to describe all animals in the category "cattle", whereas the terms "calf herd", "beef bull herd", etc. comprise the animals in the respective category.

The animals in the hypothetical herds are not "whole animals", expressed as integers. Fractions of animals are used throughout.

The death of animals may happen at any time. It is considered a stochastic event. Hence we calculate the number of animals to be fed as the mean of the numbers at the beginning and the end of the respective lifespan. We also assume that the majority of dead animals can be utilized.

[1] Losses comprise deaths due to "normal" illnesses. Losses in epidemics are excluded, as are losses by preventive culling.
[2] A "lactation" is defined as the time span between two successive calvings. This time span is a function of milk yield (see Dämmgen et al., 2012a).

2.2.1.1 Dairy cows

Although the overall number of cows is kept constant (steady state condition, 100 cow herd^{-1}), calculations require additional information and differentiate among:

- the mean population that is fed and milked,
- the number of cows at the beginning of the lactation, used for the calculation of calves born,
- the number of cows at the end of the final lactation which can be utilized by slaughtering and,
- the number of cows that are culled prematurely (and the share utilized thereof).

The relations among these numbers are obvious from the following example calculations for cow numbers in or after three lactations (Figure 2).

The number of cows in this example herd with three lactations is:

$$N_{cow} = N_{cow,1} + N_{cow,2} + N_{cow,3} \quad (1)$$

where
N_{cow} number of cows in the herd (in animal herd^{-1})
$N_{cow,1}$ number of cows in 1st lactation (in animal herd^{-1}) etc.

The numbers in the three lactations are obtained as:

$$N_{cow,1} = \frac{N_{cow}}{1 + \left(1 - x_{loss,cow,1}\right) + \left(1 - x_{loss,cow,2}\right) \cdot \left(1 - x_{loss,cow,1}\right)} \quad (2a)$$

$$N_{cow,2} = N_{cow,1} \cdot \left(1 - x_{loss,cow,1}\right) \quad (2b)$$

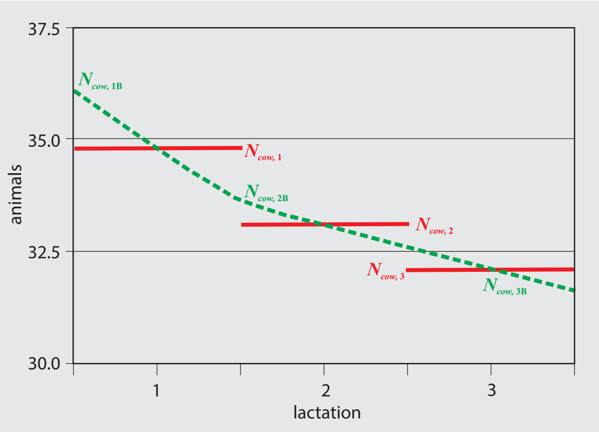

Figure 2
Clarification of animal numbers. Red lines: mean cow numbers, $N_{\text{cow n}}$, in the n-th lactation (here in 1st, 2nd and 3rd lactations), mean cow numbers, $N_{\text{cow nB}}$, at the beginning of the n-th lactation. Green dotted lines illustrate the development of numbers between the beginning and the end of a lactation period.

$$N_{\text{cow, 3}} = N_{\text{cow, 2}} \cdot (1 - x_{\text{loss, cow, 2}}) \quad (2c)$$

where
$N_{\text{cow, 1}}$ number of cows in 1st lactation (in animal herd^{-1})
N_{cow} animals in the cow herd (in animal herd^{-1})
$x_{\text{loss, cow, 1}}$ loss rate between 1st and 2nd lactations ($x_{\text{loss, cow, 1}}$ = 0.20 animal animal^{-1})
$x_{\text{loss, cow, 2}}$ loss rate between 2nd and 3rd lactations ($x_{\text{loss, cow, 2}}$ = 0.07 animal animal^{-1})

These numbers ($N_{\text{cow, 1}}$ etc.) are used to quantify feed requirements, excretions and milk produced. For 2 to 5 lactations they are collated in Tables 2 and 3.

Table 2
Composition of the cow herds as function of the number of the productive lifespan (animals fed; 10 % losses in 1st lactation, 5 % losses in subsequent lactations)

productive lifespan of dairy cows t_{pls}	cows animals in lactation no				
overall lactations	1	2	3	4	5
2	52.6	47.4			
3	36.3	32.7	31.0		
4	28.0	25.2	24.0	22.8	
5	23.0	20.7	19.7	18.7	17.8

These numbers differ from the numbers at the beginning of the respective lactation. The number of animals at the beginning of lactation n equals that of the end of lactation n-1. For details of the calculations, see Appendix 4.

Table 3
Number of cows at the beginning of a lactation as a function of the productive lifespan

productive lifespan of dairy cows t_{pls}	cows animals at the beginning of lactation no					
overall lactations	1	2	3	4	5	6
2	55.3	50.0	44.7			
3	39.1	33.5	31.8	30.3		
4	30.2	25.9	24.6	23.4	22.2	
5	24.8	21.3	20.2	19.2	18.3	17.3

The number of utilizable cows at the end of the 3rd lactation amounts to

$$N_{\text{util, cow, 3E}} = N_{\text{cow, 3}} \cdot \left(1 - \frac{x_{\text{loss, cow, 3}}}{2}\right) \quad (3)$$

where
$N_{\text{util, cow, 3E}}$ number of utilizable cows (i.e. cows that can be slaughtered) at the end of the 3rd lactation (in cow herd^{-1})
$N_{\text{cow, 3}}$ mean number of cows in the 3rd lactation (in cow herd^{-1})
$x_{\text{loss, cow, 3}}$ loss rate of cows in the 3rd lactation ($x_{\text{v, cow, 3}}$ = 0.07 cow cow^{-1})

The number of animals (culled and perished) that is utilized during the 1st lactation is:

$$N_{\text{util, cow, 1}} = N_{\text{cow 1}} \cdot x_{\text{loss, cow, 1}} \cdot x_{\text{util}} \quad (4)$$

where
$N_{\text{util, cow, 1}}$ number of utilized cows in the 1st lactation (slaughtered and culled) (in cow herd^{-1})
$N_{\text{cow, 1}}$ number of cows in the 1st lactation (in cow herd^{-1})
$x_{\text{loss, cow, 1}}$ loss rate in the 1st lactation ($x_{\text{loss, cow, 1}}$ = 0.20 cow cow^{-1})
x_{util} utilization rate of lost animals (x_{util} = 0.92 cow cow^{-1})

Other lactations are treated accordingly. Animals that cannot be utilized are taken to the knacker's yard.

2.2.1.2 Calves

We assume that each cow gives birth to one calf at the beginning of the lactation period. The number of twins is set to zero. A calving rate of 98 % accounts for losses by abortion. The number of calves born in the herd is:

$$N_{\text{calf, B}} = (N_{\text{cow, 1B}} + N_{\text{cow, 2B}} + \ldots) \cdot x_{\text{C}} \quad (5)$$

where
$N_{\text{calf, B}}$ number of calves born in the herd (in calf herd^{-1} lactation^{-1})
$N_{\text{cow, 1B}}$ number of cows at the beginning of the 1st lactation (in cow herd^{-1} lactation^{-1})

$N_{\text{cow, 2B}}$ number of cows at the beginning of the 2nd lactation (in cow herd^{-1} lactation^{-1}) etc.
x_C calving rate ($x_C = 0.98$ calf cow^{-1})

The number of surviving calves results from the number of calves born and calf losses.

$$N_{\text{calf, E}} = N_{\text{calf, B}} \cdot (1 - x_{\text{loss, calf}}) \quad (6a)$$

$$N_{\text{Fcalf, E}} = N_{\text{Fcalf, B}} \cdot (1 - x_{\text{loss, Fcalf}}) \quad (6b)$$

$$N_{\text{Mcalf, E}} = N_{\text{Mcalf, B}} \cdot (1 - x_{\text{loss, Mcalf}}) \quad (6c)$$

where
$N_{\text{calf, E}}$ number of calves at the end of their lifespan [3] (in calf herd^{-1} lactation^{-1})
$N_{\text{calf, B}}$ number of calves born (in calf herd^{-1} lactation^{-1})
$x_{\text{loss, calf}}$ loss rate of calves (in calf calf^{-1})
$N_{\text{Fcalf, E}}$ number of female calves at the end of their lifespan (in calf herd^{-1} lactation^{-1})
$N_{\text{Fcalf, E}}$ number of surviving female calves (in calf herd^{-1} lactation^{-1})
$x_{\text{loss, Fcalf}}$ loss rate of female calves (in calf calf^{-1})
$N_{\text{Mcalf, E}}$ number of male calves at the end of their lifespan (in calf herd^{-1} lactation^{-1})
$N_{\text{Mcalf, E}}$ number of surviving male calves (in calf herd^{-1} lactation^{-1})
$x_{\text{v, Mcalf}}$ loss rate of male calves (in calf calf^{-1})

The number of calves to be fed is:

$$N_{\text{calf}} = \frac{N_{\text{calf, B}} + N_{\text{calf, E}}}{2} \quad (7)$$

where
N_{calf} number of calves to be fed (in calf herd^{-1} lactation^{-1})
$N_{\text{calf, B}}$ number of calves born (in calf herd^{-1} lactation^{-1})
$N_{\text{calf, E}}$ number of surviving calves (in calf herd^{-1} lactation^{-1})

Dead calves are given to the knacker's yard.

2.2.1.3 Dairy heifers

The number of heifers needed to replace cows (so-called dairy heifers, "Dheifers") amounts to:

$$N_{\text{DH, B}} = N_{\text{cow, B1}} \cdot (1 + x_{\text{loss, DH}}) \quad (8)$$

where
$N_{\text{DH, B}}$ number of dairy heifers at the beginning of their lifespan [4] (in Dheifer herd^{-1} lactation^{-1})
$N_{\text{cow, B1}}$ number of cows at the beginning of the 1st lactation (in cow herd^{-1} lactation^{-1})
$x_{\text{v, DH}}$ loss rate of dairy heifers (in Dheifer Dheifer^{-1})

As above, the number of dairy heifers to be fed is:

[3] The lifespan of a calf ends, when it is considered a heifer or bull.
[4] The lifespan of a cow begins with her 1st lactation.

$$N_{\text{DH}} = \frac{N_{\text{cow, B1}} + N_{\text{DH, B}}}{2} \quad (9)$$

where
N_{DH} number of dairy heifers to be fed (in Dheifer herd^{-1} lactation^{-1})
$N_{\text{cow, B1}}$ number of cows to be replaced (in cow herd^{-1} lactation^{-1})
$N_{\text{DH, B}}$ number of dairy heifers at the beginning of their lifespan (in Dheifer herd^{-1} lactation^{-1})

Here we assume that 60 % of heifers lost are utilized by the butcher.

2.2.1.4 Beef heifers

The number of beef heifers depends on the number of dairy heifers required for replacement of cows. As the ratio of female and male calves is assumed to be 1, their number can be obtained from:

$$\begin{aligned} N_{\text{BH, B}} &= \frac{1}{2} \cdot N_{\text{Fcalf, E}} - N_{\text{DH, B}} \\ &= \frac{1}{2} \cdot N_{\text{Fcalf, B}} \cdot (1 - x_{\text{loss, Fcalf}}) - N_{\text{DH, B}} \end{aligned} \quad (10)$$

where
$N_{\text{BH, B}}$ number of beef heifers at the beginning of fattening (in Bheifer herd^{-1} lactation^{-1})
$N_{\text{Fcalf, E}}$ number of surviving female calves (in calf herd^{-1} lactation^{-1})
$N_{\text{DH, B}}$ number of dairy heifers at the beginning of their lifespan (in Dheifer herd^{-1} lactation^{-1})
$N_{\text{Fcalf, B}}$ number of female calves born (in calf herd^{-1} lactation^{-1})
$x_{\text{loss, Fcalf}}$ loss rate of female calves (in calf calf^{-1})

Of these the following quantity can be used for protein production:

$$N_{\text{BH, E}} = N_{\text{BH, B}} \cdot (1 - x_{\text{loss, BH}}) \quad (11)$$

where
$N_{\text{BH, E}}$ number of beef heifers at the end of the fattening period (in Bheifer herd^{-1} lactation^{-1})
$N_{\text{BH, B}}$ number of beef heifers at the beginning of the fattening period (in Bheifer herd^{-1} lactation^{-1})
$x_{\text{loss, BH}}$ loss rate for beef heifers (in Bheifer Bheifer^{-1})

The number of animals to be fed is:

$$N_{\text{BH}} = \frac{N_{\text{BH, B}} + N_{\text{BH, E}}}{2} \quad (12)$$

where
N_{BH} number of beef heifers to be fed (in Bheifer herd^{-1} lactation^{-1})
$N_{\text{BH, E}}$ number of beef heifers at the end of the fattening period (in Bheifer herd^{-1} lactation^{-1})

$N_{BH, B}$ number of beef heifers at the beginning of the fattening period (in Bheifer herd^{-1} lactation^{-1})

60 % of losses are assumed to be utilized by the butcher.

2.2.1.5 Beef bulls

At the beginning of the fattening period the number of beef bulls is:

$$N_{BB, A} = N_{Mcalf, E} \quad (13)$$

where

$N_{BB, A}$ number of beef bulls at the beginning of the fattening period (in Bbull herd^{-1} lactation^{-1})

$N_{Mcalf, E}$ number of surviving male calves (in calf herd^{-1} lactation^{-1})

For protein production the following number can be used:

$$N_{BMB, E} = N_{BB, A} \cdot (1 - x_{loss, BB}) \quad (14)$$

where

$N_{BB, E}$ number of beef bulls at the end of the fattening period (in Bbull herd^{-1} lactation^{-1})

$N_{BB, B}$ number of beef bulls at the beginning of the fattening period (in Bbull herd^{-1} lactation^{-1})

$x_{loss, BB}$ loss rate for beef bulls (in Bbull Bbull^{-1})

Again, 60 % of losses are assumed to be utilized by the butcher.

2.2.2 Animal performance

2.2.2.1 Dairy cows

This paper describes Holstein herds with high milk yields. Milk yields and composition, live weights as well as feed composition are adapted from experimental data derived from a grazing experiment described in Beeker et al. (2006).

Table 4
Dairy cows, performance data

variable	unit	1st lactation	subsequent lactations
live weight at beginning	kg cow^{-1}	625	675
final live weight	kg cow^{-1}	675	725
milk yield (nominal milk yield)*			
7000	kg cow^{-1} a^{-1}	6300	7350
8000	kg cow^{-1} a^{-1}	7200	8400
9000	kg cow^{-1} a^{-1}	8100	9450
10000	kg cow^{-1} a^{-1}	9000	10500
11000	kg cow^{-1} a^{-1}	9900	11550
milk fat content	kg kg^{-1}	0.0395	0.0405
milk protein content	kg kg^{-1}	0.0333	0.0330

* Nominal milk yield is the mean 305 day yield (according to German practice) of 1st, 2nd and 3rd lactations.

Here, animal performance data for animals housed during summer did not differ from those of grazed animals. The data in Table 4 are used for our calculations.

Feed intake and excretion rates are calculated according to Dämmgen et al. (2009, 2012a). The N content of the whole cow is set to 0.025 kg kg^{-1} (DLG, 2014).

2.2.2.2 Calves

"Standard calves" of the German national emission inventory (described in Dämmgen et al., 2013) are used. Their final weights are 125 kg calf^{-1}.

2.2.2.3 Dairy heifers

The start weight of dairy heifers is the final weight of calves (125 kg calf^{-1}), their final weights the start weight of dairy cows (625 kg cow^{-1}). The mean weight gain is 685 g Dheifer^{-1} d^{-1}. Dairy heifers may be grazed in the 2nd summer of their lives. The age of first calving is 27 months, reflecting German practice. The model used to quantify energy requirements and feed intake is described in Dämmgen et al. (2015 b); feed composition data are taken from Weiss et al. (2005).

2.2.2.4 Beef heifers

Heifers not needed for replacement are fattened and sold as beef heifers. We assume a constant weight gain of 1000 g Bheifer^{-1} d^{-1} and a final weight of 535 kg Bheifer^{-1}. Detailed information on the model will be found in Dämmgen et al. (in preparation). There, ME intake rates agree with information provided by Steinwidder (2012) for intensive fattening. The N content of weight gained is 0.025 kg kg^{-1} (DLG, 2014).

2.2.2.5 Beef bulls

All male cattle are fattened. In accordance with convention, we set the start of fattening to a weight of 175 kg bull^{-1}. We fixed the final weight to 675 kg bull^{-1} and the weight gain to 1250 g bull^{-1} d^{-1}. The gap between standard calf and beef bull is closed by assuming mean ME requirements of 50 MJ bull^{-1} d^{-1} (KTBL, 2014). A customary mix of grass silage, maize silage and concentrates ("Rindermastfutter") is fed (Frickh et al., 2002, Kirchgeßner et al., 2008). The N content of weight gained is 0.025 kg kg^{-1} in accordance with DLG (2014).

2.2.3 Grazing

The grazing period is set to 180 d a^{-1}. Dairy cows are grazed 8 h d^{-1}, dairy heifers 24 h d^{-1}.

2.2.4 Protein produced

2.2.4.1 Milk protein

The amount of milk protein **produced** per lactation is:

$$Y_{XP, milk} = \begin{pmatrix} N_{cow,1} \cdot Y_{milk,1} \cdot x_{XP, milk,1} \\ + N_{cow,2} \cdot Y_{milk,2} \cdot x_{XP, milk,2} \end{pmatrix} \cdot \gamma \quad (15)$$

where

$Y_{XP, milk}$ protein produced with milk (in Mg herd^{-1} lactation^{-1})
$N_{cow, 1}$ number of cows milked in 1st lactation (cow herd^{-1} lactation^{-1})
$Y_{milk, 1}$ milk yield in 1st lactation (in kg cow^{-1} lactation^{-1})
$x_{XP, milk, 1}$ protein content of milk in 1st lactation (in kg kg^{-1})
$N_{cow, 2}$ number of cows milked in subsequent lactations (cow herd^{-1} lactation^{-1})
$Y_{milk, 1}$ milk yield in subsequent lactations (in kg cow^{-1} lactation^{-1})
$X_{XP, milk, 2}$ protein content of milk in subsequent lactations (in kg kg^{-1})
γ unit conversion factor for mass units (γ = 0.001 Mg kg^{-1})

For milk yields and protein contents see Table 4.

The decisive entity in our calculations is the amount of milk **sold**, which additionally takes into account the milk fed to calves, the reduced milk yields during illnesses and the milk that has to be discharged due to contamination. Hence, the amount of milk marketed is:

$$Y_{XP, milk, mark} = Y_{XP, milk} - \left(\Delta Y_{XP, milk, calf} + \Delta Y_{XP, milk, depr} + \Delta Y_{XP, milk, dis}\right) \quad (16)$$

where

$Y_{XP, milk, mark}$ marketable milk protein (in Mg herd^{-1} lactation^{-1})
$Y_{XP, milk}$ produced milk protein (in Mg herd lactation^{-1})
$\Delta Y_{XP, milk, calf}$ milk protein fed to calves (in Mg herd^{-1} lactation^{-1})
$\Delta Y_{XP, milk, depr}$ milk protein not produced due to yield depression caused by illness (in Mg herd^{-1} lactation^{-1})
$\Delta Y_{XP, milk, dis}$ discharged milk protein due to contamination (in Mg herd^{-1} lactation^{-1})

The amount fed to calves is:

$$\Delta Y_{XP, milk, calf} = N_{calf} \cdot m_{milk, calf} \cdot \left(x_{XP, milk, 1} \cdot t_1 + \left(t_{pls} - t_1\right) \cdot x_{XP, milk, 2}\right) \cdot \frac{1}{t_{pls}} \quad (17)$$

where

$Y_{XP, milk, calf}$ milk protein fed to calves (in Mg herd^{-1} lactation^{-1})
N_{calf} number of calves to be fed (in calf herd^{-1} lactation^{-1})
$m_{milk, calf}$ milk fed to calves ($m_{milk, calf}$ = 387 kg calf^{-1})
$x_{XP, milk, 1}$ protein content of milk in 1st lactation ($x_{XP, milk, 1}$ = 0.0333 kg kg^{-1})
t_1 timespan of 1st lactation (t_1 = 1 lactation)
t_{pls} productive lifespan of cows (in lactation)
$x_{XP, milk, 2}$ protein content of milk in 2nd lactation ($x_{XP, milk, 2}$ = 0.0330 kg kg^{-1})

Sick cows produce less milk than healthy ones. This yield depression is depending on the type and frequency of illness and the age of the cow. [5] It is quantified as follows:

$$\Delta Y_{depr, n} = Y_{milk, n} \cdot I_{sick, n} \cdot x_{depr, n} = Y_{milk, n} \cdot X_{depr, n} \quad (18)$$

where

$\Delta Y_{depr, n}$ yield reduction caused by mastitis and other illnesses in n-th lactation (in Mg herd^{-1} lactation^{-1})
$Y_{milk, n}$ nominal milk yield in n-th lactation (in Mg herd^{-1} lactation^{-1})
$I_{sick, n}$ incidence for mastitis and other illnesses in n-th lactation (in cow cow^{-1})
$x_{depr, 1}$ yield depression related to incidences in n-th lactation (in kg kg^{-1})
$X_{depr, n}$ cumulative yield depression in n-th lactation (in kg kg^{-1})

The relevant entities are collated in Table 5.

Non-marketable milk contains pathogens or medicine (including metabolites). It is discharged to the slurry store. By far the most frequent illness is mastitis. Rudolphi et al. (2012) evaluated data from almost 38000 lactations in Mecklenburg-Vorpommern; the share of discharged milk was 2.2 %.

We decided that half the incidences result in non-marketable milk (see Hogeveen, 2005; Spohr, 2005; Hellerich, 2008). Non-marketable milk amounts to:

Table 5
Incidences and yield depression rates for diseased cows (high losses *) (for the deviation of the data set see Appendix 1)

lactation number	frequency of illness (incidence)	relative yield depression*	fraction of cows whose treatment results in non-marketable milk **	fraction of non-marketable milk
	$I_{sick, n}$	$X_{depr, n}$	½ $I_{sick, n}$	$X_{milk, dis, n}$
	cow cow^{-1}	kg kg^{-1}	cow cow^{-1}	kg kg^{-1}
1st	0.713	0.0139	0.357	0.0113
2nd	0.771	0.0334	0.386	0.0104
3rd	0.771	0.0315	0.386	0.0101
4th and more	0.881	0.0295	0.441	0.0117

* data base: Rudolphi et al. (2012);
** assumptions due to missing experimental data: 50 % of all treatments result in non-marketable milk

[5] Yield is also a function of ambient temperature and humidity. However, these parameters are not taken into account.

$$\Delta Y_{\text{milk, dis, n}} = Y_{\text{milk, n}} \cdot \frac{1}{2} \cdot I_{\text{sick, n}} \cdot x_{\text{milk, dis, n}} \cdot N_{\text{cow, n}} = Y_{\text{milk, n}} \cdot X_{\text{milk, dis, n}} \cdot N_{\text{cow, n}} \quad (19)$$

where

$\Delta Y_{\text{milk, dis, n}}$ amount of milk discharged due to illnesses in n-th lactation (in Mg herd^{-1} lactation^{-1})

$Y_{\text{milk, n}}$ milk yield of animals in n-th lactation (in Mg cow^{-1} lactation^{-1})

$I_{\text{sick n}}$ frequency of relevant illnesses n-th lactation (in cow cow^{-1})

$x_{\text{milk, dis, n}}$ incidence related fraction of milk that has to be discharged in n-th lactation (in kg kg^{-1})

$N_{\text{cow, n}}$ number of cows in n-th lactation (in cow herd^{-1})

$X_{\text{milk dis, n}}$ overall fraction of milk that has to be discharged in n-th lactation (in kg kg^{-1})

Non-marketable milk is discharged to the slurry store. Volatile solids (VS) and N contributions to the respective amounts in slurry are accounted for. For further details see Appendix 2.

2.2.4.2 Meat protein

The amounts of edible meat protein produced with meat are obtained as follows:

$$Y_{\text{P, meat, i}} = w_{\text{fin, i}} \cdot x_{\text{cd, i}} \cdot x_{\text{XP, i}} \quad (20)$$

where

$Y_{\text{XP, meat, i}}$ meat protein per utilized animal and category i (in kg animal^{-1})

$w_{\text{fin, i}}$ final weight of an animal in category i (in kg animal^{-1})

$x_{\text{cd, i}}$ carcass dressing percentage in category i (in kg kg^{-1})

$x_{\text{XP, i}}$ protein content of utilized carcasses in category i (in kg kg^{-1})

Carcass dressing percentages as evaluated in Dämmgen et al. (2015 c) are listed in Table 6.

Table 6
Carcass dressing percentage, carcass and meat protein weights

	final weight	carcass dressing percentage	carcass weights	meat protein
	kg animal^{-1}	%	kg animal^{-1}	kg animal^{-1}
cows (utilized)	725	47.4	390.1	60.9
beef heifers	535	47.5	285.5	44.6
beef bulls	675	55.0	391.5	61.2

2.3 Feed properties

The quantification of excretions presupposes the knowledge of feed properties. In this paper, we use the same values as in the national emission inventory; they were taken from DLG (1997) and Beyer et al. (2004). They are collated in Table 7.

2.4 Determination of excretion and emissions rates

2.4.1 Excretion rates

All matter leaving the animals' bodies is treated as excretion, i.e. CH_4 and CO_2 from digestion processes as well as organic matter ("volatile solids") and N excreted with urine and faeces. By convention, CO_2 from digestion (and subsequent stages of the manure management) is not treated as emission to be accounted for, as this amount was fixed by photosynthesis (see Chapter 2.1). However, this does not apply to the CO_2 released from lime in feed.

2.4.1.1 Methane from enteric fermentation

CH_4 excretions (emissions) from enteric fermentations were quantified using the respective procedures in the national emission inventory calculations (for dairy cows see Dämmgen et al., 2012a, for calves Dämmgen et al., 2013, for dairy heifers Dämmgen et al., 2015b, for beef heifers and bulls Dämmgen et al., in preparation). In contrast to IPCC (2006b), emission rates are not deduced from gross energy (GE) intake rates but from the feed intake rates and specific feed properties according to Kirchgessner et al. (1994).

2.4.1.2 Carbon dioxide

As stated above, CO_2 from respiration of animals and microbes is not considered a relevant emission. Emissions from lime in feed have to be dealt with. In principle, the amounts of lime needed as nutrients can be estimated from the overall calcium (Ca) balance of the herd. Here, a simpler approach is chosen:

Ca is supplied with concentrates. Its overall amounts are governed by the requirements of dairy cows. For these, a share of 0.01 kg kg^{-1} lime (considered to be pure calcium carbonate, $CaCO_3$) is considered normal (LfL, 2014). This approach is then transferred to the other animal categories.

Hence we derive the amounts and emissions as follows:

$$E_{\text{CO2, Flime, herd}} = EF_{\text{CO2, calcite}} \cdot M_{\text{Flime, herd}} \quad (21)$$

$$M_{\text{Flime, herd}} = M_{\text{conc, herd}} \cdot x_{\text{CaCO3, conc}} \quad (22)$$

where

$E_{\text{CO2, Flime, herd}}$ CO_2 emissions of the herd originating from lime in feed (Flime) (in Mg herd^{-1} lactation^{-1} CO_2)

$EF_{\text{CO2, calcite}}$ CO_2 emission factor for calcite ($EF_{\text{CO2, calcite}}$ = 0.44 kg kg^{-1})

$M_{\text{Flime, herd}}$ amount of lime in feed (in Mg herd^{-1} lactation^{-1})

$M_{\text{conc, herd}}$ amount of concentrates fed (in Mg herd^{-1} lactation^{-1})

$x_{\text{CaCO3, conc}}$ lime content of concentrates ($x_{\text{CaCO3, conc}}$ = 0.01 kg kg^{-1})

Table 7
Feed properties (DLG, 1997, and Beyer et al., 2004)

	DM	GE	ME	NEL		ash	fibre	NfE	protein	fat
					X_{DOM}	X_{ash}	X_{Fi}	X_{NfE}	X_{XP}	X_F
	kg kg^{-1}	MJ kg^{-1}	MJ kg^{-1}	MJ kg^{-1}	MJ MJ^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}
barley	0.88	18.60	12.90	8.20	0.88	0.025	0.110	0.730	0.115	0.035
oat	0.87	19.14	11.29	7.36	0.73	0.035	0.120	0.665	0.130	0.050
maize (grain)	0.87	18.88	13.86	9.65	0.90	0.017	0.027	0.802	0.117	0.037
triticale	0.87	18.26	13.06	8.95	0.87	0.021	0.023	0.807	0.134	0.015
wheat	0.87	18.50	13.20	9.00	0.880	0.020	0.030	0.785	0.145	0.020
wheat bran	0.88	19.14	10.76	6.80	0.71	0.055	0.100	0.625	0.175	0.045
linseed extraction meal	0.90	19.55	11.92	7.54	0.79	0.070	0.105	0.425	0.380	0.020
rape seed extraction meal	0.91	19.24	11.39	7.12	0.79	0.080	0.150	0.345	0.400	0.020
sugar beets shreds	0.90	18.20	11.90	7.40	0.80	0.055	0.200	0.645	0.095	0.005
sugar beets shreds molasses	0.90	17.49	11.78	7.77	0.86	0.075	0.155	0.660	0.105	0.005
molasses	0.77	15.23	11.47	7.63	0.85	0.110	0.000	0.840	0.050	0.000
standard concentrate (MLF 18/3)	0.79	18.70	12.30	7.60	0.83	0.067	0.117	0.557	0.218	0.042
mineral supplements	1.00									
pasture grass 1	0.18	17.90	10.00	6.30	0.72	0.105	0.215	0.450	0.190	0.040
pasture grass 2	0.18	18.00	10.45	6.27	0.74	0.089	0.247	0.445	0.152	0.039
grass silage	0.35	18.50	10.00	6.30	0.72	0.099	0.245	0.452	0.162	0.042
maize silage	0.35	17.99	10.70	6.45	0.73	0.045	0.201	0.641	0.081	0.032
hay	0.86	18.00	9.50	5.50	0.68	0.115	0.270	0.400	0.180	0.035
straw	0.85	18.10	6.40	3.80	0.47	0.070	0.450	0.425	0.038	0.017

2.4.2 Manure management and resulting emissions of CH_4, NH_3, NO, N_2O und N_2, biogas carbon credit

The guidelines for the construction of national emission inventories for GHG and the N species relevant for mass balances (IPCC, 2006b; EMEP, 2013) are used in modified versions reflecting the national situation (Dämmgen et al., 2012b). If necessary, excretions are split into excretions in the house and on pasture, using the respective times spent indoors as the key.

In Germany, considerable amounts of slurry are treated in biogas plants, as a rule in co-fermentation with other substrates. The amount of CH_4 produced herein is taken to be the maximum CH_4 producing capacity (IPCC, 2006b; KTBL, 2010). In this work, we use the entire volume of CH_4 released to produce electricity with Otto gas engines [6] and alternators. The fermented slurry is assumed to be stored in gas-tight tanks.

In Dämmgen et al. (2016a), the share of digested slurry is a variable in the scenarios considered.

Our calculations make use of the following constants:

energy content (calorific value) of CH_4	50 MJ kg^{-1}
electrical efficiency	38 %
energy units transformation factor	0.2778 kWh MJ^{-1}

Feed into the national grid yields a credit in the national GHG balance as it substitutes electric energy produced with fossil fuels. Our calculations take this into account by subtracting the same amount of GHG from the balance that would be released by its conventional generation (i.e. 0.595 kg kWh^{-1} CO_2-eq).

The conditions in the digester favour the mineralization of organic N which leads to increased NH_4-N contents in slurry. In addition, the pH of slurry increases. Biogas slurries have a higher NH_3 vapour pressure than undigested slurry. However, due to lack of reliable information there are no specific NH_3 emission factors for untreated slurry to estimate emissions from slurry application.

2.4.3 Greenhouse gas potentials

Emissions of CO_2, CH_4 and N_2O have an adverse effect on the energy balance of the atmosphere, albeit with different intensities. This is reflected by the use of their respective global warming potentials (GWP) which state how efficient a gas is in comparison with CO_2. GWP depends on the time span considered. For standard calculations, it is customary to use a time span of 100 a. IPCC (2007) propose:

GWP_{CH4} = 25 kg kg^{-1}

GWP_{N2O} = 298 kg kg^{-1}

Cumulative GHG emissions are therefore given in so-called CO_2 equivalents (CO_2-eq).

[6] In contrast to other engines (e.g. pilot injection engines), the gas Otto engine does not need extra fuel.

2.5 Production of forage crops

The calculation of the amounts of feeds is based on energy requirements, expressed as metabolizable energy (ME) or net energy lactation (NEL) requirements for each livestock category. Together with the respective diet composition and the yields of the forage crops, the cropped areas can be deduced.

2.5.1 Feed requirements

Step 1 is the calculation of the respective energy requirements for each livestock category as a function of their performance. The methods applied are described in Dämmgen et al. (2009) for dairy cows, Dämmgen et al. (2013) for calves, Dämmgen et al. (2015b) for dairy heifers and Dämmgen et al. (in preparation) for beef heifers and bulls.

The overall area needed to produce a single crop is calculated from the yield per unit area, considering losses. If the seeds are fed in concentrates, the amounts of seed needed to cultivate the crop have to be taken into account.

For crops where generative parts (seeds) are fed, the area needed for cultivation is quantified using Equation (23a). If conserved forage (e.g. silage) is fed, this is accounted for in Equation (23b). Crops whose vegetative parts (leaves or roots) are fed are treated in Equation (23c). The respective constants for seed requirements and conservation are listed in Tables 8 and 9.

$$A_{\mathrm{j,\,veg}} = \frac{M_{\mathrm{FM,\,j}}}{Y_{\mathrm{j}} \cdot x_{\mathrm{DM,\,j}}} \cdot \left(1 + x_{\mathrm{w,\,j}}\right) \cdot \gamma_{\mathrm{F}} \cdot f_{\mathrm{all,\,j}} \qquad (23a)$$

$$A_{\mathrm{j,\,sil}} = \frac{M_{\mathrm{FM,\,j}} \cdot \left(1 + x_{\mathrm{KV,\,j}}\right)}{Y_{\mathrm{j}} \cdot x_{\mathrm{DM,\,j}}} \cdot \left(1 + x_{\mathrm{w,\,j}}\right) \cdot \gamma_{\mathrm{F}} \cdot f_{\mathrm{all,\,j}} \qquad (23b)$$

$$A_{\mathrm{j,\,gen}} = \frac{M_{\mathrm{FM,\,j}}}{\left(Y_{\mathrm{j}} - M_{\mathrm{SG,\,j}}\right) \cdot x_{\mathrm{DM,\,j}}} \cdot \left(1 + x_{\mathrm{w,\,j}}\right) \cdot \gamma_{\mathrm{F}} \cdot f_{\mathrm{all,\,j}} \qquad (23c)$$

where

$A_{\mathrm{j,\,veg}}$	area for a crop j where vegetative parts are used (in ha herd^{-1} lactation^{-1})
$M_{\mathrm{FM,\,j}}$	required amount of a feed constituent (fresh matter) produced from a crop j (in Mg herd^{-1} lactation^{-1} FM)
Y_{j}	mean yield of a crop j (in Mg ha^{-1} a^{-1} FM
$x_{\mathrm{DM,\,j}}$	dry matter content of a crop j (in kg kg^{-1})
$x_{\mathrm{w,\,j}}$	fraction that is wasted (in kg kg^{-1})
$f_{\mathrm{all,\,j}}$	allocation factor for joint products (in ha ha^{-1}) (see Chapter. 2.5.5)
$A_{\mathrm{j,\,sil}}$	area for a crop j before conservation (in ha herd^{-1} lactation^{-1})
$x_{\mathrm{KV,\,j}}$	conservation losses (in kg kg^{-1})
$A_{\mathrm{j,\,gen}}$	area for a crop j whose generative parts are used (in ha herd^{-1} lactation^{-1})
$M_{\mathrm{SG,\,j}}$	fraction of harvest that has to be used as seed (in Mg ha^{-1} a^{-1} FM)
γ_{F}	assumed time units conversion factor for feed production (γ_{F} = 1 lactation a^{-1})

We assume that the feed required for one lactation is produced in one vegetation period.

In accordance with the rules of good practice, feed is not wasted. Feed that has not been utilized by dairy cows is used to feed other cattle, in particular dairy heifers. It appears justified to assume that $x_{w, j}$ = 0 kg kg^{-1} (expert judgement U. Meyer).

2.5.2 Conservation losses during drying and ensiling

2.5.2.1 Drying – hay making

Losses during the production of hay comprise those from mowing (1 to 5 % DM), from leaching after rain events (up to 15 %), from crumbling during gathering (up to 10 %) as well as losses during storage (see Appendix 3, Table A6). The losses used in this paper are shown in Table 8.

2.5.2.2 Ensiling and conservation losses

Losses in the production of silage comprise losses on the field as well as losses from ensiling, storage and during removal of silage from the store. Losses on the field depend on the duration of wilting and weather conditions, being increased by rainfall. Fermentation during ensiling (of grass and maize) leads to some losses of organic matter and energy (ME or NEL): the heterolactic formation of lactic acid produces CO_2 from the degradation of sugars and other simple carbohydrates (fructose, glucose, citrate, maleate) (e.g. McGechan, 1990). Further losses result from the penetration of oxygen into the silage and from loss of liquids (effluent). Losses strongly increase with decreasing dry matter contents and from the fermentation process itself, in particular from the application of an inoculant. Silage exposed to oxygen must be rejected during emptying of the store. It is then stored separately and treated (stored, applied) in the same way as solid manure. For details, in particular conservation losses, see Appendix 3.

Table 8
Conservation losses considered in this work

feed	overall losses * kg kg^{-1} DM	losses during emptying kg kg^{-1} DM
grass silage	0.18	0.20
grass clover silage	0.17**	0.20
maize silage	0.14	0.20
hay	0.20***	

*comprises conservation and emptying;
** inoculation is presupposed;
*** includes transport losses

2.5.3 Seeding material

Some of the harvest of cereals and oilseeds has to be used as seeding material. [7] This fraction is determined as follows:

$$M_{SG, j} = d_{SG, j} \cdot TGW_j \cdot \gamma_1 \cdot \gamma_2 \cdot \eta \quad (24)$$

where

$M_{SG, j}$ fraction of harvest crop used as seeding material (in Mg ha^{-1} a^{-1} FM)
$d_{SG, j}$ sowing density for a crop j (in grains m^{-2}, see Table 9)
TGW_j 1000 grain weight of a crop j (in kg (1000 grains)$^{-1}$, see Table 9)
γ_1 conversion factor for single grain masses (γ_1 = 1·10^{-3} kg kg^{-1})
γ_2 conversion factor for mass units (γ_2 = 1·10^{-3} Mg kg^{-1})
η conversion factor for area units (η = 10000 m^2 ha^{-1})

The relevant masses and sowing densities in Table 9 are taken from KTBL (2014) (the respective means of the ranges provided therein).

Table 9
Properties of seeding material and amounts needed for sowing

	1000 grain weight kg (1000 grain)$^{-1}$			sowing density grain m^{-2}			mass of seeds required Mg ha^{-1} a^{-1}
	from	to	mean	from	to	mean	
winter barley	0.043	0.054	0.0485	220	350	285	0.138
oats	0.030	0.045	0.0375	260	450	355	0.133
maize	0.200	0.450	0.3250	7	10	8.5	0.028
triticale	0.034	0.048	0.0410	250	350	300	0.123
winter wheat	0.040	0.055	0.0475	200	400	300	0.143

2.5.4 Crop yields and fertilizer requirements

We use mean crop yields reported by official statistics for Mecklenburg-Vorpommern and the years 2007 to 2012 with the exception of oil flax. The latter are taken from Graf et al. (2005). Dry matter contents of all crops are taken from Beyer et al. (2004). Data are listed in Table 10.

[7] This work assumes that all processes dealt with happen on a single farm. Hence the production of seeding material is included.

Table 10
Yields and fertilizer requirements

	mean yield (FM) *	DM content	mean yield (DM)	fertilizer N **	lime***
	$Mg\ ha^{-1}\ a^{-1}$	$kg\ kg^{-1}$	$Mg\ ha^{-1}\ a^{-1}$	$kg\ ha^{-1}\ a^{-1}$	$Mg\ ha^{-1}\ a^{-1}$
barley	6.80	0.880	5.99	177	1.0
oat	4.96	0.880	4.36	122	1.0
grain maize	9.85	0.880	8.67	213	1.0
triticale	5.80	0.880	5.10	178	1.0
wheat	8.23	0.880	7.24	213	1.0
linseed	1.50	0.910	1.37	93	0.0
rapeseed	3.68	0.880	3.24	190	1.0
sugar beet	65.1	0.230	14.98	170	1.0
pasture grass	48.0	0.180	8.64	290	0.0
grass for silage	53.6	0.180	9.65	249	0.0
maize for silage	47.4	0.350	16.58	207	1.3

* data for Mecklenburg-Vorpommern (StatBA, 2014 ff, means for 2007 to 2012).
** Calculated according to German fertilizer enactment ("Düngeverordnung", DüV; DüV, 2007).
*** Lime as separate treatment (sweetener). Further lime inputs with calcium ammonium nitrate and in connection with acidifying N fertilizers such as urea. For details see Chapter 2.5.9.2.

2.5.5 Consideration of joint products – allocation of areas for cultivation

The areas needed for joint products such as rape seed extraction meal or wheat bran are treated separately as an allocation of the emissions has to be drawn up. Allocation makes use of the gross energy (GE) contents of the joint products. The results are compiled in Table 11.

$$f_{\text{äll, j}} = X_{\text{fc, j}} \cdot \frac{\eta_{\text{GE, fc, j}}}{\eta_{\text{GE, crop, j}}} \tag{25}$$

where
$f_{\text{all, j}}$ allocation factor for emissions from feed constituents from the production of a crop j (in kg kg^{-1} MJ MJ^{-1})
$X_{\text{fc, j}}$ mass fraction of the relevant feed constituent (in kg kg^{-1} DM)
$\eta_{\text{GE, fc, j}}$ GE content of the feed constituent (in MJ kg^{-1})
$\eta_{\text{GE, F, j}}$ GE content of crop j (in MJ kg^{-1})

The resulting area of cultivation that has to be considered in emission determinations is:

$$E_{\text{X, j, all}} = E_{\text{X, j}} \cdot f_{\text{all, j}} \tag{26}$$

where
$E_{\text{X, j, all}}$ fraction of emissions of a trace gas X that is allocated to crop j (in kg $herd^{-1}$ $lactation^{-1}$)
$E_{\text{X, j}}$ emissions from the cultivation of a crop j (in kg $herd^{-1}$ $lactation^{-1}$)
$f_{\text{all, j}}$ allocation factor for a feed constituent produced from a crop j (in kg kg^{-1} MJ MJ^{-1})

2.5.6 Energy requirements in plant production (diesel fuel)

The diesel fuel needed to operate tractors and other machinery is compiled in Table 12 for standard procedures in conventional farming including ploughing. Data are taken from KTBL (2014).

$$B_{\text{DF}} = \sum A_{\text{j}} \cdot V_{\text{DF, j}} \tag{27}$$

where
B_{DF} diesel fuel required (in l $herd^{-1}$ a^{-1})
A_{j} cultivated area for crop j (in ha $herd^{-1}$ a^{-1})
$V_{\text{DF, j}}$ volume of diesel fuel consumed per area for the production of a crop j (in l ha^{-1})

Table 11
Allocation factors *

feed constituent	crop	mass fraction of harvested product	GE content crop	GE content feed constituent	allocation factor
		$X_{\text{FB, j}}$	$\eta_{\text{GE, F, j}}$	$\eta_{\text{GE, FB, j}}$	$f_{\text{all, j}}$
		$kg\ kg^{-1}$	$MJ\ kg^{-1}$	$MJ\ kg^{-1}$	$kg\ kg^{-1}\ MJ\ MJ^{-1}$
linseed extraction meal	linseed	0.629	26.75	19.55	0.460
rapeseed extraction meal	rapeseed	0.575	27.82	19.24	0.398
wheat bran	wheat grains	0.260	18.50	19.14	0.269
sugar beet shreds	sugar beet	0.277	15.83	18.19	0.318
sugar beet shreds molasses	sugar beet	0.370	15.83	17.49	0.409
molasses	sugar beet	0.027	15.83	15.23	0.026

* see Appendix 5 for further information. GE contents from Beyer et al. (2004).

Table 12
Diesel fuel consumption per ha (rounded values)

crop	diesel V_{DF} l ha^{-1}	crop	diesel V_{DF} l ha^{-1}
cereals	82.9	pasture grass	28.6
grain maize	81.6	silage grass	78.1
linseed	34.7	maize for silage	88.9
rapeseed	51.4		
sugar beet	96.8	hay	106.5

2.5.7 Fertilizer N requirements and mineral fertilizer consumption

2.5.7.1 Requirements

In principle, N requirements of the crops are to be quantified using the element balance (Figure 1), accounting for mean yields and including sources such as N fixation by legumes and atmospheric deposition. However, the German fertilizer enactment (DüV, 2007) does not consider deposition; it accounts for a share of inputs with manure N (expressed as mineral fertilizer equivalent) and it allows excess fertilization of up to 60 kg ha^{-1} a^{-1} N. In regions where Holstein cattle are used, these 60 kg ha^{-1} a^{-1} are exploited in practice (see Appendix 6).

The amounts of mineral fertilizer N applied are calculated as follows:

$$M_{NMF} = \left(\sum M_{F,N,j} - M_{NMa} \cdot f_{MFE} + \left(M_{AD} + M_{DEx}^{*} \right) \cdot \sum A_j \right) \cdot \gamma_F \qquad (28)$$

where

M_{NMF} N applied with mineral fertilizer (in kg herd^{-1} lactation^{-1})
$M_{F,N,j}$ N required by crop j (in kg herd^{-1} lactation^{-1})
M_{NMa} N input with manures (in kg herd^{-1} lactation^{-1})
f_{MFE} mineral fertilizer equivalent (in kg kg^{-1})
M_{AD} atmospheric N deposition (in kg ha^{-1} lactation^{-1})
M_{Dex}^{*} excess N input (in kg ha^{-1} lactation^{-1})
A_j cultivated area of a crop j (in ha herd^{-1} lactation^{-1})
γ_F assumed time conversion factor for the cultivation of crops for feed production (γ_F = 1 lactation a^{-1})

According to the fertilizer enactment, the amount of N required by crops is quantified as follows:

$$M_{F,N,j} = \frac{B_j}{x_{DM,j} \cdot Y_j} \cdot M_{E,j} \qquad (29)$$

where
$M_{F,N,j}$ N fertilizer required for crop j (in kg herd^{-1} lactation^{-1})
B_j amount of crop j required (DM) (in kg herd^{-1} lactation^{-1})
$x_{DM,j}$ dry matter content of crop j (in kg kg^{-1})
Y_j mean yield of crop j (fresh matter, FM) (in kg ha^{-1} a^{-1})
$M_{E,j}$ recommended yield-dependent amount of N fertilizer for a crop j (related to FM) (in kg ha^{-1} a^{-1})

and

$$M_{E,j} = M_{F,N,DüV,j} \cdot \left(Y_{exp,j} - Y_{DüV,j} \right) \cdot f_{corr,DüV,j} \qquad (30)$$

where
$M_{E,j}$ yield dependent amount of N fertilizer recommended by German fertilizer enactment (Düngeverordnung, DüV) for a crop j (related to FM) (in kg ha^{-1} a^{-1})
$M_{F,N,DüV,j}$ recommended standard amount of N fertilizer for mean yield to be applied to crop j (in kg ha^{-1} a^{-1} N) [8]
$Y_{exp,j}$ expected yield of crop j (in Mg ha^{-1} DM) (see Table 10)
$Y_{DüV,j}$ standard yield of crop j used in the enactment (in Mg ha^{-1} a^{-1} DM)
$f_{corr,DüV,j}$ correction factor used in the enactment to adjust fertilizer amounts to yields (in kg Mg^{-1})

DüV correction factors are 15 kg Mg^{-1} for cereals and linseed, 7.5 kg Mg^{-1} for rapeseed, 1.5 kg Mg^{-1} for sugar beet, 3 kg Mg^{-1} for silage maize and 26 kg Mg^{-1} for grass.

Atmospheric N deposition is provided by the German Environment Agency (UBA, 2015a, data base for 2009). For rural regions in Northern Germany so-called background deposition inputs for pastures and arable land amounts to

Table 13
Duration of N uptake by crops, share of individual growth period $x_{AD,j}$ (data from KTBL, 2014, adjusted)

	growth period beginning	harvest	fraction of growth period $x_{AD,j}$ (in a a^{-1})
winter cereals	September to November	July and August	0.83
winter rapeseed	August	July	0.95
grain maize	April	October	0.58
silage maize	April	September/October	0.56
sugar beet	March	September/October	0.60
oil flax	April	September	0.50
grassland (pastures, hay meadows)	utilized for several years		0.95

[8] The recommended fertilizer amounts those suggested by the N balance (Figure 1) by far.

15 kg ha^{-1} a^{-1} N. For crops whose vegetation period is less than 1 a, a correction is applied.

$$M_{\mathrm{AD}} = \sum M_{\mathrm{AD,\,j}} \quad (31)$$

$$M_{\mathrm{AD,\,j}} = M_{\mathrm{AD,\,r}} \cdot A_{\mathrm{j}} \cdot x_{\mathrm{AD,\,j}} \quad (32)$$

where

M_{AD} atmospheric N deposition (in kg herd^{-1} a^{-1})
$M_{\mathrm{AD,\,j}}$ atmospheric N deposition for a crop j (in kg herd^{-1} a^{-1})
$M_{\mathrm{AD,\,r}}$ mean regional deposition to short vegetation (in kg ha^{-1} a^{-1})
A_{j} area cultivated for crop j (in ha herd^{-1} lactation^{-1})
$x_{\mathrm{AD,\,j}}$ fraction of year considered as growth period for crop j (in a a^{-1})

With respect to these data, it appears practical to use a constant amount of 10 kg ha^{-1} a^{-1} N for the whole farm considered in this work to simplify the calculation process.

2.5.7.2 Mineral fertilizer type applied

Mineral fertilizers differ with respect to their NH_3 emissions. Hence, detailed calculations should also refer to the type of fertilizer used. However, the German fertilizer enactment does not mention the fertilizer types to which their data is related. The authors' impression is that the recommended amounts are in any case "on the safe side". On the contrary, a balance orientated approach should consider NH_3 emissions.

This work is without a strict balance-orientated calculation due to the many potential pitfalls. In Dämmgen et al. (2016a) the N balance is used to value different fertilizer regimes. The knowledge of fertilizer types is a prerequisite for emissions calculations. In Table 14, the frequency distribution of mineral fertilizers in Mecklenburg-Vorpommern is presented together with the fertilizer-specific NH_3 emission factors.

Table 14

Shares of various N fertilizers sold in Mecklenburg-Vorpommern (related to N, mean for years 2010 to 2014) (StatBA, 2014) and NH_3 emission factors (related to N applied) (EMEP, 2013)

mineral fertilizer	fertilizer sold % of N	$EF_{\mathrm{NH3,\,MF,\,k}}$ kg NH_3 (kg N)$^{-1}$
calcium ammonium nitrate (CAN)	26.4	0.022
urea ammonium nitrate solution (UAN)	6.9	0.125
urea (U)	37.4	0.243 *
other straight fertilizers	22.5	0.022 **
NP fertilizer	5.5	0.113
NK and NPK fertilizer	1.3	0.037

* The urea emission factor is controversial and under discussion. We use the emission factors for urea and UAN as in the national emission inventory (Haenel et al., 2016).
** In accordance with the national inventory the value for CAN is used.

2.5.8 Direct emissions from mineral fertilizer application

2.5.8.1 N species released after mineral fertilizer application

Application of mineral N fertilizers leads to emissions of NH_3, NO, N_2O and N_2. The emissions are related to the amounts of the different fertilizers using specific emission factors (see Table 14). Emissions are quantified in different ways according to the different guidance documents (IPCC, 2006b; EMEP, 2013). For NH_3 emissions, the relation used is:

$$E_{\mathrm{NH3,\,MF}} = \sum E_{\mathrm{NH3,\,MF,\,k}} \quad (33)$$

$$E_{\mathrm{NH3,\,MF,\,k}} = EF_{\mathrm{NH3,\,MF,\,k}} \cdot M_{\mathrm{MF,\,k}} \cdot \gamma_{\mathrm{NH3}} = EF_{\mathrm{NH3,\,MF,\,k}} \cdot M_{\mathrm{MF}} \cdot x_{\mathrm{MF,\,k}} \cdot \gamma_{\mathrm{NH3}} \quad (34)$$

where

$E_{\mathrm{NH3,\,MF}}$ overall NH_3 emissions from mineral fertilizer application (in kg herd^{-1} lactation^{-1} NH_3)
$E_{\mathrm{NH3,\,MF,\,k}}$ NH_3 emissions from application of fertilizer k (in kg herd^{-1} lactation^{-1} NH_3)
$EF_{\mathrm{NH3,\,MF,\,k}}$ emission factor for mineral fertilizer k (in kg NH_3 (kg N)$^{-1}$)
$M_{\mathrm{MF,\,k}}$ amount of mineral fertilizer k applied (in kg herd^{-1} lactation^{-1} N)
γ_{NH3} stoichiometric conversion factor (γ_{NH3} = 17/14 kg kg^{-1} kmol kmol^{-1})
M_{MF} overall amount of mineral fertilizer applied (in kg herd^{-1} lactation^{-1} N)
$x_{\mathrm{MF,\,k}}$ share of mineral fertilizer k (related to N) (in kg kg^{-1})

For NO emissions, EMEP (2013) provides a simple methodology which determines emissions irrespective of the fertilizer used.

$$E_{\mathrm{NO,\,MF}} = EF_{\mathrm{NO,\,MF}} \cdot \gamma_{\mathrm{NO}} \cdot \sum_{k=1}^{n} M_{\mathrm{MF,\,k}} \quad (35)$$

where

$E_{\mathrm{NO,\,MF}}$ NO emissions from mineral fertilizer application (in kg herd^{-1} lactation^{-1} NO)
$EF_{\mathrm{NO,\,MF}}$ NO-N emission factor for mineral fertilizer application ($EF_{\mathrm{NO,\,MF}}$ = 0.026 kg kg^{-1} N)
γ_{NO} stoichiometric conversion factor (γ_{NO} = 30/14 kg kg^{-1} kmol kmol^{-1})
$M_{\mathrm{MF,\,k}}$ amount of mineral fertilizer k applied (in kg herd^{-1} lactation^{-1} N)

N_2O emissions are quantified from N inputs without any consideration of (comparatively rapid) NH_3 emissions using the methodology provided in IPCC (2006b).

$$E_{\mathrm{N2O,\,MF}} = EF_{\mathrm{N2O,\,MF}} \cdot \gamma_{\mathrm{N2O}} \cdot \sum_{k=1}^{n} M_{\mathrm{MF,\,k}} \quad (36)$$

where

$E_{\mathrm{N2O,\,MF}}$ N_2O emissions after mineral fertilizer application (in kg herd^{-1} lactation^{-1} N_2O)

$EF_{N2O, MF}$ N_2O-N emission factor for mineral fertilizer ($EF_{N2O, MF}$ = 0.01 kg kg^{-1} N_2O-N)
γ_{N2O} stoichiometric conversion factor (γ_{N2O} = 44/28 kg kg^{-1} kmol kmol^{-1})
$M_{MF, k}$ amount of mineral fertilizer k applied (in kg herd^{-1} lactation^{-1} N)

Equation (36) is applied by analogy to N_2 emissions. The emission factor used $EF_{N2, MF}$ 0.03 kg kg^{-1} N_2, i.e. thrice $EF_{N2O, MF}$. (For background information see Haenel et al. (2016) and the literature cited therein.)

2.5.8.2 CO_2 emissions from urea

The complete hydrolysis of urea releases half a mol CO_2 for each mol N applied.

These emissions have to be considered as follows:

$$E_{CO2, U} = EF_{CO2, U} \cdot \left(M_U + x_{U, UAN} \cdot M_{UAN}\right) \tag{37}$$

where
$E_{CO2, U}$ CO_2 emissions from the application of urea (in kg herd^{-1} lactation^{-1} CO_2)
$EF_{CO2, U}$ emission factor ($EF_{CO2, U}$ = 44/(2 · 14) kg kg^{-1} kmol kmol^{-1})
M_U amount of urea applied (in kg herd^{-1} lactation^{-1} N)
$x_{U, UAN}$ share of urea in UAN ($x_{U, UAN}$ = 0.5 kg kg^{-1} N for customary fertilizers)
M_{UAN} amount of UAN applied (in kg herd^{-1} lactation^{-1} N)

The application of CAN also leads to CO_2 emissions. These are treated as emissions from liming (Chapter 2.5.9).

2.5.8.3 N species emitted from the application of livestock manures

Emissions from manure N are related to the amounts of N (M_{NMa}) entering soil. These are quantified in the calculations of matter fluxes in manure management of the various livestock categories. The IPCC (2006b) methodology uses the approach as in Equation (36) with the same emission factor ($EF_{N2O, Ma}$ = $EF_{N2O, MF}$ = 0.01 kg kg^{-1}). In accordance with the national emission inventory NO and N_2 emissions are determined using emission factors of one tenth and three times that of N_2O: $EF_{NO-N, Ma}$ = 0.1 $EF_{N2O-N, Ma}$; $EF_{N2, Ma}$ = 3 $EF_{N2O-N, Ma}$).

2.5.9 Emissions from the application of lime

2.5.9.1 Composition of limestone

Lime used to reduce soil acidity (soil sweetener, S_{lime}) contains variable proportions of $CaCO_3$ and $MgCO_3$, other minerals and small quantities of water. This work assumes a composition of 0.80 kg kg^{-1} $CaCO_3$ (calcite) and 0.05 kg kg^{-1} $MgCO_3$ (magnesite). CO_2 emissions are related to these shares as in Equation (38).

$$CaCO_3 \longrightarrow CaO + CO_2$$
$$MgCO_3 \longrightarrow MgCO_3 + CO_2$$

$$E_{CO2, Slime} = \begin{pmatrix} x_{calcite} \cdot EF_{CO2, calcite} \\ + x_{magnesite} \cdot EF_{CO2, magnesite} \end{pmatrix} \cdot M_{Slime} = EF_{CO2, Slime} \cdot M_{Slime} \tag{38}$$

where
$E_{CO2, Slime}$ CO_2 emissions from lime applied (in kg herd^{-1} lactation^{-1} CO_2)
$x_{calcite}$ calcite fraction in lime ($x_{calcite}$ = 0.80 kg kg^{-1})
$EF_{CO2, calcite}$ CO_2 emission factor for calcite ($EF_{CO2, calcite}$ = 0.44 kg kg^{-1})
$x_{magnesite}$ magnesite fraction in lime ($x_{magnesite}$ = 0.05 kg kg^{-1})
$EF_{CO2, magnesite}$ CO_2 emission factor for magnesite ($EF_{CO2, magnesite}$ = 0.52 kg kg^{-1})
M_{Slime} amount of lime applied (in kg herd^{-1} lactation^{-1})
$EF_{CO2, Slime}$ overall CO_2 emission factor for lime ($EF_{CO2, Slime}$ = 0.38 kg kg^{-1})

2.5.9.2 Additional liming to compensate for acidifying properties of certain mineral fertilizers – "Kalkwert"

The calculation of additional lime application in this work follows KTBL (2014). The amounts recommended there are based on N fertilization with CAN. In order to compensate for its acidifying properties 55 kg CaO per 100 kg N have to be applied. However, these are obviously contained in the amount of lime in KTBL standard applications. For fertilizers with an increased acidifying capacity such as urea or UAN a correction application of 100 kg CaO per 100 kg N is necessary ("Kalkwert"). For these fertilizers, the amounts of lime increase by 45 kg CaO or 80 kg $CaCO_3$ or 94 kg of lime per 100 kg N (LWK-NRW, 2015). No data are available for other fertilizers. In accordance with the NH_3 emission factors they are treated in the same way as CAN.

The additional lime amounts to:

$$M_{Slime, N} = \left(M_{MF, UAN} + M_{MF, U}\right) \cdot f_{lime, N} \tag{39}$$

where
$M_{Slime, N}$ additional lime amount cause by acidifying N fertilizers (in kg herd^{-1} lactation^{-1})
$M_{MF, UAN}$ amount of UAN applied (in kg herd^{-1} lactation^{-1} N)
$M_{MD, U}$ amount of urea applied (in kg herd^{-1} lactation^{-1} N)
$f_{lime, N}$ correction factor ($f_{lime, N}$ = 0.8 kg (kg N)$^{-1}$ $CaCO_3$)

2.5.9.3 Calcium ammonium nitrate as source of CO_2 emissions

As a rule, amounts of CAN applied are given as amounts of N. However, CAN contains 0.24 kg kg^{-1} lime in addition to 0.27 kg kg^{-1} N. Hence, emissions are to be quantified using Equation (40).

$$E_{CO2, CAN} = M_{N, CAN} \cdot \frac{x_{lime, CAN}}{x_{N, CAN}} \cdot EF_{CO2, Slime} \tag{40}$$

where

$E_{CO2, CAN}$ CO_2 emission from the application of CAN (in Mg herd^{-1} lactation^{-1} CO_2)
$M_{N, CAN}$ amount of CAN applied (in Mg herd^{-1} lactation^{-1} N)
$x_{lime, CAN}$ lime content of CAN ($x_{lime, CAN}$ = 0.24 kg kg^{-1})
$x_{N, CAN}$ N content of CAN ($x_{N, CAN}$ = 0.27 kg kg^{-1})
$EF_{CO2, Slime}$ CO_2 emission factor for lime ($EF_{CO2, Slime}$ = 0.38 kg kg^{-1})

2.5.10 Emissions from crop residues

Decaying crop residues release N_2O, NO and N_2. No method to quantify NO emissions is provided by EMEP (2013) or IPCC (2006b). N_2O and N_2 emissions are treated in the same way as emissions from fertilizers. However, the amounts of above and below ground biomass liable to decay have to be determined as follows:

$$E_{N2O, CR} = EF_{N2O, CR} \cdot M_{CR} \cdot \gamma_{N2O} \quad (41)$$

where

$E_{N2O, CR}$ N_2O emissions from crop residues (in kg herd^{-1} lactation^{-1} N_2O)
$EF_{N2O, CR}$ N_2O emission factor for crop residues ($EF_{N2O, CR}$ = 0.01 kg kg^{-1} N_2O)
M_{CR} N in crop residues (in kg herd^{-1} lactation^{-1} N)
γ_{N2O} stoichiometric conversion factor (γ_{N2O} = 44/28 kg kg^{-1} kmol kmol^{-1})

and

$$M_{CR} = \sum_j A_j \cdot x_{renew, j} \cdot x_{mow, j} \cdot Y_j \cdot \left(x_{Y, DM, j} + a_{above, j} \cdot x_{DM, below, j}\right) \cdot a_{below} \cdot x_{N, below} \quad (42)$$

where

M_{CR} amounts of N in crop residues (in Mg herd^{-1} lactation^{-1} N)
A_j area cultivated with crop j (in ha herd^{-1} lactation^{-1})
$x_{renew, j}$ share of the crop j that is harvested annually (in ha ha^{-1})
$x_{mow, j}$ 1 / number of harvests of crop j per year (dimensionless)
Y_j yield of crop j (FM) (in Mg ha^{-1})
$x_{Y, DM, j}$ dry matter content of crop j (in kg kg^{-1})
$a_{above, j}$ share of above ground plant residues related to amount harvested (in kg kg^{-1})
$x_{DM, above, j}$ dry matter content of above ground parts of crop j (in kg kg^{-1})
$a_{below, j}$ share of below ground plant residues related to the amount harvested (in kg kg^{-1})
$x_{N, below, j}$ N content of below ground residues related to DM (in kg kg^{-1} N)

Variables are collated in Table 15. For crop yields see Table 10.

2.6 Emissions from the provision of mineral fertilizers and lime

This work considers those emissions from the production of mineral fertilizers containing nitrogen, phosphorus and potassium as well as lime (feed and soil) that are released during the production process itself, e.g. NH_3 and particulate NH_4NO_3 from the production of ammonium nitrate. It also deals with emissions related to the use of fossil fuels for fertilizer production. We refer to Jenssen and Kongshauk (2003) as well as EMEP (2013) for short descriptions of the processes involved.

2.6.1 Ammonium nitrate

Ammonium nitrate (AN, NH_4NO_3) is the neutralisation product of nitric acid (HNO_3) and NH_3.

The ammonia synthesis (Haber Bosch process) is the starting point of the entire N fertilizer production process. The process is energy intensive. However, the NH_3 emission factor

Table 15
Variables used for the determination of N_2O emissions from crop residues

	x_{renew} ha ha^{-1}	x_{mow}	$x_{Y, DM, j}$ kg kg-1	$x_{AGR, DM, j}$ kg kg^{-1}	$a_{above, j}$ kg kg^{-1}	$x_{N, above, j}$ kg kg^{-1} N	$a_{below, j}$ kg kg^{-1}	$x_{N, below, j}$ kg kg^{-1} N
barley	1	1	0.86	0.86	0.7	0.0050	0.22	0.014
oat	1	1	0.86	0.86	1.1	0.0050	0.25	0.008
grain maize	1	1	0.86	0.86	1.0	0.0038	0.22	0.007
triticale	1	1	0.86	0.86	0.9	0.0050	0.22	0.008
wheat	1	1	0.86	0.86	0.8	0.0050	0.23	0.009
oil flax	1	1	0.91	0.86	1.5	0.0053	0.22	0.010
rape	1	1	0.91	0.86	1.7	0.0070	0.22	0.010
sugar beet	1	1	0.23	0.18	0.7	0.0040	0.20	0.014
pasture grass	0.1	0.33	0.20	0.20	0.3	0.0050	0.80	0.012
silage grass	0.4	0.33	0.28	0.28	0.0	0.0038	0.22	0.007
silage maize	1	1	0.20	0.20	0.3	0.0048	0.80	0.012

as preliminary product in the AN synthesis is so small that it is ignored. In contrast, NO emissions have to be accounted for.

The other reactant, HNO_3, originates from an aqueous solution of nitrogen oxides generated by combustion of NH_3. Intermediate reactions release N_2O. EMEP (2013) provides emission factors for NH_3, NO_2 and for particles (total suspended particles, TSP) (see Table 16). GHG emissions can also be quantified (Brentrup and Pallière, 2008).

2.6.2 Calcium ammonium nitrate

CAN is obtained from well ground limestone added to molten NH_4NO_3. The product contains 0.27 kg kg^{-1} N and 0.24 kg kg^{-1} lime. No emission factors are available for this process. However, the overall emissions from CAN production may be determined as follows:

$$E_{\text{NH3, CAN}} = EF_{\text{NH3, CAN}} \cdot M_{\text{NH4-N, CAN}} \cdot \gamma_{\text{NH3}} \quad (43)$$

$$E_{\text{NH4-N, CAN}} = EF_{\text{NH4-N, CAN}} \cdot M_{\text{NH4-N, CAN}} \quad (44)$$

$$E_{\text{NO3-N, CAN}} = EF_{\text{NO3-N, CAN}} \cdot M_{\text{NO3-N, CAN}} \quad (45)$$

where

$E_{\text{NH3, CAN}}$ gaseous NH_3 emission from CAN production (in kg herd^{-1} lactation^{-1})
$EF_{\text{NH3, CAN}}$ NH_3 emission factor for CAN production ($EF_{\text{NH3, CAN}}$ = 0.030 kg kg^{-1})
$M_{\text{NH4-N, CAN}}$ amount of NH_4-N in CAN applied (in kg herd^{-1} lactation^{-1})
γ_{NH3} stoichiometric conversion factor (γ_{NH3} = 17/14 kg kg^{-1} kmol kmol^{-1})
$E_{\text{NH4-N, CAN}}$ particulate NH_4-N emission from CAN production (in kg herd^{-1} lactation^{-1})
$EF_{\text{NH4-N, CAN}}$ emission factor for particulate NH_4-N for CAN production ($EF_{\text{NH4-N, CAN}}$ = 0.035 kg kg^{-1})
$E_{\text{NO3-N, CAN}}$ particulate NO_3-N emission from CAN production (in kg herd^{-1} lactation^{-1})
$EF_{\text{NO3-N, CAN}}$ emission factor for particulate NO_3-N for CAN production ($EF_{\text{NO3-N, CAN}}$ = 0.035 kg kg^{-1})
$M_{\text{NO3-N, CAN}}$ amount of NO_3-N in CAN applied (in kg herd^{-1} lactation^{-1})

The amounts of NH_4-N and NO_3-N are obtained according to:

$$M_{\text{NO3-N, CAN}} = M_{\text{NH4-N, CAN}} = \frac{1}{2} M_{\text{N, CAN}} \quad (46)$$

where

$M_{\text{NH4-N, CAN}}$ amount of NH_4-N in CAN applied (in kg herd^{-1} lactation^{-1})
$M_{\text{NO3-N, CAN}}$ amount of NO_3-N in CAN applied (in kg herd^{-1} lactation^{-1})
$M_{\text{N, CAN}}$ amount of N in CAN applied (in kg herd^{-1} lactation^{-1})

NH_3 emission can only occur simultaneously with HNO_3 emission, which will be deposited immediately and next to its source and will not be transmitted to ambient air.

The amount of AN as precursor of CAN is then determined as:

$$M_{\text{AN-N}} = \left(1 + \left(EF_{\text{NH3, CAN}} + EF_{\text{NH4-N, CAN}}\right)\right) \cdot M_{\text{N, CAN}} \quad (47)$$

where

$M_{\text{AN-N}}$ amount of AN used as educt in CAN production (in kg herd^{-1} lactation^{-1})
$EF_{\text{NH3, CAN}}$ NH_3 emission factor (gaseous) for CAN production ($EF_{\text{NH3, CAN}}$ = 0.030 kg kg^{-1})
$EF_{\text{NH4-N, CAN}}$ NH_4-N emission factor (particulate) for CAN production ($EF_{\text{NH4-N, CAN}}$ = 0.035 kg kg^{-1})
$M_{\text{N, CAN}}$ amount of CAN applied as fertilizer (in kg herd^{-1} lactation^{-1})

The amount of HNO_3-N needed for the AN synthesis is:

$$M_{\text{HNO3-N}} = \frac{1}{2} M_{\text{AN-N}} \cdot \left(1 + EF_{\text{NO2-N, HNO3}}\right) \quad (48)$$

where

$M_{\text{HNO3-N}}$ amount of N in HNO_3 for AN synthesis (in kg herd^{-1} lactation^{-1})
$M_{\text{AN-N}}$ amount of the NH_4NO_3-N to be produced

Table 16
Emission factors for the compounds emitted in the manufacture of nitrogen fertilizers (N species from EMEP, 2013; GHG from Brentrup and Pallière, 2008)

	NH_3 kg kg^{-1}	NO_2 kg kg-1	NH_4-N particulate* kg kg^{-1}	NO_3-N particulate kg kg^{-1}	GHG ** kg kg^{-1} CO_2-eq	notes
ammonia	0.00001	0.001	---	---		
nitric acid	---	0.010	---	---		***
ammonium nitrate	0.030		0.035	0.035	1.18	****
calcium ammonium nitrate	---	---	---	---	1.00	
urea	0.0025				5.15	

* calculated from TSP (total suspended particles) emissions;
** related to the final product, includes precursors.
*** NO_2 emission related to HNO_3 produced.
**** The emission factor provided for TSP is 0.2 kg kg^{-1}; NH_4NO_3-TSP contains 0.35 kg kg^{-1} N. Hence the emission factor for N with TSP is 0.070 kg kg^{-1}.

(in kg herd^{-1} lactation^{-1})
$EF_{\text{NO2-N, HNO3}}$ emission factor for NO_2 in HNO_3 production (EF_{NO2} = 0.010 kg kg^{-1} related to HNO_3)

$$EF_{\text{NO2-N, HNO3}} = EF_{\text{NO2, HNO3}} \cdot \frac{\gamma_{\text{HNO3}}}{\gamma_{\text{NO2}}} \quad (49)$$

where
$EF_{\text{NO2-N, HNO3}}$ emission factor for NO_2-N in HNO_3 production (in kg kg^{-1}, related to N)
$EF_{\text{NO2, HNO3}}$ emission factor for NO_2 in HNO_3 production (EF_{NO2} = 0.010 kg kg^{-1}, related to HNO_3)
γ_{HNO3} stoichiometric conversion factor (γ_{HNO3} = 63/14 kg kg^{-1} kmol kmol^{-1})
γ_{NO2} stoichiometric conversion factor (γ_{NO2} = 46/14 kg kg^{-1} kmol kmol^{-1})

2.6.3 Urea

In Germany, urea is produced in a combination of NH_3 synthesis (synthesis gas process, e.g. Kellogg process) and a high pressure urea synthesis (e.g. Stamicarbon process). Natural gas, air and water are reactants in the NH_3 synthesis:

$$9\,CH_4 + 12\,H_2O + 3\,O_2 + 10\,N_2 \longrightarrow 9\,CO_2 + 20\,NH_3$$

The reaction of NH_3 with CO_2 consumes more CO_2 than is released in NH_3 formation: urea production is a sink for CO_2.

$$20\,NH_3 + 9\,CO_2\,(\text{from } H_2\text{ - synthesis}) + 1\,CO_2\,(\text{additional}) \longrightarrow 10\,(H_2N)_2CO + 10\,H_2O$$

2.6.4 Emissions from the production of NP fertilizers

The most common NP fertilizer is di-ammonium phosphate (DAP). The pure compound, $(NH_4)_2HPO_4$, has 0.21 kg kg^{-1} N and 0.54 kg kg^{-1} P_2O_5. The technical product has less nutrients. Brentrup and Pallière (2008) give 0.18 kg kg^{-1} N.

EMEP (2013) provides an emission factor for TSP, from which an emission factor for NH_4-N can be deduced. Brentrup and Pallière (2008) report a GHG emission factor for DAP. From this data emissions can be calculated as follows:

$$E_{\text{NH4-N, DAP}} = M_{\text{DAP}} \cdot EF_{\text{TSP, DAP}} \cdot x_{\text{N, DAP}} \quad (50)$$

where
$E_{\text{NH4-N, DAP}}$ particulate NH_4-N emissions from the production of DAP (in kg herd^{-1} lactation^{-1})
M_{DAP} amount of DAP applied (in kg herd^{-1} lactation^{-1})
$EF_{\text{TSP, DAP}}$ DAP emission factor for particles (TSP) ($EF_{\text{TSP, DAP}}$ = 0.0003 kg kg^{-1})
$x_{\text{N, DAP}}$ N in DAP ($x_{\text{N, DAP}}$ = 0.18 kg kg^{-1})

$$E_{\text{GHG, DAP}} = M_{\text{DAP}} \cdot EF_{\text{GHG, DAP}} \quad (51)$$

where
$E_{\text{GHG, DAP}}$ GHG emissions during the production of DAP (in kg herd^{-1} lactation^{-1} CO_2-eq)
M_{DAP} amount of DAP-N applied (in kg herd^{-1} lactation^{-1})
$EF_{\text{GHG, DAP}}$ GHG emission factor ($EF_{\text{GHG, DAP}}$ = 11.27 kg (kg^{-1} N) CO_2-eq)

NPK fertilizers are characterized by their N content. The emissions are calculated in the same way as for DAP.

2.6.5 Emissions from the provision of P and K fertilizers

For the production of crops, KTBL (2014) recommends the application of P and K fertilizer which are characterized by their respective P and K contents, given as P_2O_5 and K_2O. Brentrup and Pallière (2008) provide GHG emission factors for triple superphosphate ($Ca(H_2PO_4)_2{\cdot}H_2O$) and potash (KCl), from which emissions can be deduced:

$$E_{\text{GHG, P2O5, j}} = A_j \cdot M_{\text{PKF}} \cdot x_{\text{P2O5}} \cdot EF_{\text{P2O5}} \quad (52)$$

$$E_{\text{GHG, K2O, j}} = A_j \cdot M_{\text{PKF}} \cdot x_{\text{K2O}} \cdot EF_{\text{K2O}} \quad (53)$$

where
$G_{\text{GHG, P2O5, j}}$ GHG emissions from P fertilizers applied to a crop j (in kg herd^{-1} lactation^{-1} CO_2-eq)
A_j area cultivated with crop j (in ha herd^{-1} lactation^{-1})
M_{PKF} PK fertilizer applied (taken from KTBL, 2014) (in kg ha^{-1})
x_{P2O5} P_2O_5 content of PK fertilizer (in kg kg^{-1})
EF_{P2O5} GHG emission factor for P_2O_5 production (EF_{P2O5} = 0.56 kg kg^{-1} CO_2-eq)
and
x_{K2O} K_2O content of PK fertilizer (in kg kg^{-1})
EF_{K2O} GHG emission factor for K_2O production (EF_{K2O} = 0.43 kg kg^{-1} CO_2-eq)

2.6.6 Lime

Quarrying of lime, the subsequent crushing, grinding and screening are energy intensive processes. Scholz et al. (1994) reported that 0.032 GJ Mg^{-1} diesel fuel, 0.007 GJ Mg^{-1} in explosives and 192 MJ Mg^{-1} of electrical energy are needed for these operations. [9]

2.7 Emissions from combustion engines and boilers

2.7.1 Diesel engines

Diesel engines are used in crop production. Mean area-related fuel consumptions are available for most crops (see Table A2). Diesel fuel is also used in lime production or the drying of oilseeds.

Emissions of CH_4 and CO_2 can be determined using information provided in IPCC (2006a) and of NH_3 and NO_x in EMEP (2013).

[9] Scholz et al. (1994) do not mention particle sizes.

2.7.1.1 Carbon dioxide emissions

CO_2 emissions can be quantified according to Equations (54) and (55):

$$E_{CO2,\,DF} = \sum E_{CO2,\,DF,\,j} \qquad (54)$$

$$E_{CO2,\,DF,\,j} = EF_{CO2,\,DF} \cdot A_j \cdot V_{DF,\,j} \cdot \eta_{E,\,DF} \cdot \rho_{DF} \cdot \beta \qquad (55)$$

where

$E_{CO2,\,DF}$ CO_2 emissions from diesel fuel combustion (in kg herd^{-1} lactation^{-1} CO_2)
$E_{CO2,\,DF,\,j}$ CO_2 emissions from fuel combustion for the production of crop j (in kg herd^{-1} lactation^{-1} CO_2)
$EF_{CO2,\,DF}$ CO_2 emission factor for diesel fuel combustion ($EF_{CO2,\,DF}$ = 74.1 kg GJ^{-1})
A_j area cultivated for crop j (in ha herd^{-1} lactation^{-1})
$V_{DF,\,j}$ area related fuel consumption for a crop j (in l ha^{-1})
ρ_{DF} density of diesel fuel (ρ_{DF} = 0.83 kg l^{-1})
$\eta_{E,\,DF}$ calorific value of diesel fuel ($\eta_{E,\,DF}$ = 35.73 MJ l^{-1})
β conversion factor for energy units (β = 0.001 GJ MJ^{-1})

2.7.1.2 Methane and nitrous oxide

Calculations of CH_4 and N_2O emissions from the combustion of diesel are made by analogy using:

$EF_{CH4,\,DF}$ CH_4 emission factor for diesel fuel combustion ($EF_{CH4,\,DF}$ = 0.00415 kg GJ^{-1})
$EF_{N2O,\,DF}$ N_2O emission factor for diesel fuel combustion ($EF_{N2O,\,DF}$ = 0.0286 kg GJ^{-1})

2.7.1.3 Ammonia and nitrogen oxides

EMEP (2013) reports emission factors related to the state of the art. This work uses emission factors for Stage III according to EU legislation (EU, 2004).

$$E_{NH3\text{-}N,\,DF} = \sum M_{DF,\,j} \cdot EF_{NH3,\,DF} \cdot \gamma_{NH3} \qquad (56)$$

$$E_{NOx\text{-}N,\,DF} = \sum M_{DF,\,j} \cdot EF_{NOx\text{-}N,\,DF} \cdot \gamma_{NO2} \qquad (57)$$

where

$E_{NH3\text{-}N,\,DF}$ NH_3-N emission from diesel fuel combustion (in Mg herd^{-1} lactation^{-1})
$M_{DF,\,j}$ amount of diesel fuel used for the production of crop j (in kg ha^{-1})
$EF_{NH3,\,DF}$ NH_3 emission factor for diesel fuel combustion ($EF_{NH3,\,DF}$ = 8 g Mg^{-1})
γ_{NH3} stoichiometric factor for NH_3-N emissions (γ_{NH3} = 14/17 kg kg^{-1} kmol kmol^{-1})
$E_{NOx\text{-}N,\,DF}$ NO_x-N emission from diesel fuel combustion (in Mg herd^{-1} lactation^{-1})
$EF_{NOx,\,DF}$ NO_x emission factor for diesel fuel combustion ($EF_{NOx,\,DF}$ = 13594 g Mg^{-1})
γ_{NO2} stoichiometric factor for NO_2-N emission (γ_{NO2} = 46/14 kg kg^{-1} kmol kmol^{-1})

2.7.2 Natural gas fired boilers

Sugar beet factories use natural gas or heavy fuel oil as an energy source. This work assumes natural gas as sole source. Fritsche (2003) published a GHG emission factor for CH_4 provision to characterize the mix of origins of natural gas used in Germany of 0.432 kg kWh^{-1} CO_2-eq. We used this factor to calculate the CH_4 emissions from energy use in sugar beet factories.

2.8 Emissions from processing of feeds

2.8.1 Kibbling of cereals

The specific energy consumption for kibbling depends on species and DM content. It is appropriate to use 5 kWh Mg^{-1} as mean energy requirement (expert judgement H. Kleine Klausing).

2.8.2 Production of rape and linseed extraction meals

Rapeseed and linseed extraction meals are joint products of the production of rapeseed and linseed oils. BIOGRACE (2012) gives specific energy consumption numbers for a selection of fossil fuels (Table 17).

Table 17
Energy consumption of processes in rapeseed oil and expeller meal production

	electrical energy			natural gas			diesel (heating oil)		
production step	amount	unit	related to	amount	unit	related to	amount	unit	related to
drying	0.0019	MJ MJ^{-1}	oil				0.00018	MJ MJ^{-1}	seed
grinding	0.0118	MJ MJ^{-1}	oil						
extraction	0.0011	MJ MJ^{-1}	oil	0.062	MJ MJ^{-1}	oil			
total	0.0140	MJ MJ^{-1}	oil	0.062	MJ MJ^{-1}	oil	0.00018	MJ MJ^{-1}	seed
	0.0241	MJ MJ^{-1}	seed						
equivalent to	0.572	MJ kg^{-1}	seed	0.901	MJ kg^{-1}	seed	0.00430	MJ kg^{-1}	seed
	15.9	kWh Mg^{-1}	seed						

This allows for the determination of direct emissions as follows:

$$E_{CO2, NG} = EV_{CO2, NG} \cdot EF_{CO2, NG} \quad (58)$$

where

$E_{CO2, NG}$ CO_2 emission resulting from combustion of CH_4 in boilers (in kg GJ^{-1})
$EV_{CH4, NG}$ consumption of CH_4 for combustion in boilers (in kg GJ^{-1})
$EF_{CO2, NG}$ CO_2 emission factor for CH_4 combustion in boilers (IPCC, 2006a: $EF_{CO2, NG}$ = 56.1 kg GJ^{-1})

Analogous equations are applied to determine CH_4 and N_2O emissions. EMEP (2013) provides data for the calculation of NO_x emissions.

$EF_{CH4, NG}$ CH_4 emission factor for CH_4 combustion in boilers (IPCC, 2006a: $EF_{CH4, NG}$ = 0.001 kg GJ^{-1})
$EF_{N2O NG}$ N_2O emission factor for CH_4 combustion in boilers (IPCC, 2006a: $EF_{N2O, NG}$ = 0.001 kg GJ^{-1})
$EF_{NOx NG}$ NO_x emission factor for CH_4 combustion in boilers (EMEP, 2013: $EF_{NOx, NG}$ = 0.047 kg GJ^{-1})

A comparable methodology for calculation of emissions from the respective linseed processes is not available. However, the essential properties of linseed are similar to those of rapeseed; the technology applied is identical. It is justified to treat linseed in the same way as rapeseed (expert judgement G. Brantkatschk).

2.8.3 Production of sugar beet shreds and molasses

Typically, sugar beet factories use combined heat and power. The boiler house consumes 175 kWh per Mg of sugar beet. The drying of beet shreds requires a further 75 kWh Mg^{-1} (Südzucker, 2014b). We assume that natural gas is also used as the fuel for this process. It is state of the art to forward the exhaust vapours (containing NH_3) from juice purification to the firebox of the shreds dryer. Hence, no NH_3 emissions have to be accounted for.

2.9 Provision of electric energy, diesel fuel and natural gas

Electrical energy is used for many purposes in livestock buildings (lighting, milking, milk cooling, ventilation, manure scrubbing, etc.). It is also required for the provision of water in livestock and plant production.

2.9.1 Direct energy consumption in keeping livestock

KTBL (2014) provides data for electric energy requirements for the keeping of cattle. For dairy cows, dairy heifers and beef cattle 50, 10 and 20 kWh place^{-1} a^{-1} are listed, respectively. [10]

[10] "place" stands as a unit for "livestock place".

2.9.2 Energy requirements for the provision of water

2.9.2.1 Drinking water for dairy cows

The relation given in Meyer et al. (2004) for water requirements of lactating Holstein cows is extrapolated to cover a year.

$$M_{Wt, DC} = \alpha \cdot \delta \cdot (a + b \cdot t + c \cdot Y_M + d \cdot w_{DC} + e \cdot m_{Na}) \quad (59)$$

where

$M_{Wt, DC}$ annual drinking water requirements of a dairy cow (in m^3 cow^{-1} a^{-1})
α conversion factor for time units (α = 365 d a^{-1})
δ conversion factor for units of volume (δ = 1/1000 m^3 l^{-1})
a constant (a = -26.12 l cow^{-1} d^{-1})
b coefficient (b = 1.516 l cow^{-1} d^{-1} K^{-1})
t ambient temperature (t = 20 °C)
c coefficient (c = 1.299 l kg^{-1} cow^{-1})
Y_M mean milk yield (in kg cow^{-1} d^{-1})
d coefficient (d = 0.058 l kg^{-1} d^{-1})
w_{DC} mean live weight of the cow (in kg cow^{-1})
e coefficient (e = 406 l kg^{-1})
m_{Na} mean Na uptake (in kg cow^{-1} d^{-1})

Sodium (Na) uptake is related to milk yield. Table 4.1.1 in GfE (2001) (10 pairs of values) can be transformed to Equation (60) (r^2 = 0.998):

$$m_{Na} = f + g \cdot Y_M \quad (60)$$

where

m_{Na} mean Na uptake (in kg cow^{-1} d^{-1})
f constant (f = 0.0077 kg cow^{-1} d^{-1})
g coefficient (g = 0.000677)
Y_M mean milk yield (in kg cow^{-1} d^{-1})

2.9.2.2 Drinking water for dairy and beef heifers

KTBL (2009) lists values for daily drinking water requirements as a function of animal weights (4 pairs of values). The resulting steady function (Equation (62), r^2 = 0.993) allows for the determination of the water requirements of the animal.

$$M_{Wt, He} = \theta_{He} \cdot \delta \cdot (h + l \cdot w_{He}) \quad (61)$$

where

$M_{Wt, He}$ dinking water requirements of a heifer (in m^3 heifer^{-1})
θ_{He} duration of the lifespan spent as heifer (in d)
δ conversion factor for units of volume (δ = 1/1000 m^3 l^{-1})
h constant (h = 6.458 l heifer^{-1} d^{-1})
l coefficient (l = 0.0728 l kg^{-1} d^{-1})
w_{He} mean live weight of a heifer (in kg heifer^{-1})

With the performance data listed above, water requirements of 24.1 m^3 Dheifer^{-1} and 11.4 m^3 Bheifer^{-1} can be obtained for dairy and beef heifers, respectively.

2.9.2.3 Drinking water for calves

The same table in KTBL (2009) allows for an estimate of the drinking water required for the "standard calf" used in this work. A mean amount of 10 l calf^{-1} d^{-1} adds up to 1.25 m^3 calf^{-1} in a lifespan of 125 d.

2.9.2.4 Drinking water for beef bulls

Meyer et al. (2006) quantified drinking water requirements of beef bulls and gave the following Equation (62):

$$M_{\mathrm{Wt,\,BB}} = \theta_{\mathrm{BB}} \cdot \delta \cdot \frac{1}{\rho_{\mathrm{W}}} \cdot \left(p + q \cdot t + r \cdot m_{\mathrm{DM}} + s \cdot x_{\mathrm{rough}} + u \cdot x_{\mathrm{DM,\,rough}} + v \cdot w_{\mathrm{BB}}\right) \tag{62}$$

where

$M_{\mathrm{Wt,\,BB}}$ drinking water requirements of a beef bull (in m^3 bull^{-1})
θ_{BB} duration of the lifespan of a beef bull (in d)
δ conversion factor for units of volume (δ = 1/1000 m^3 l^{-1})
ρ_{W} density of water (ρ_{W} = 1.00 kg l^{-1}
p constant (p = -3.85 kg bull^{-1} d^{-1})
q coefficient (q = 0.507 kg^{-1} bull^{-1} d^{-1} K^{-1})
t temperature in house (t = 20 °C)
r coefficient (r = 1.494)
m_{DM} dry matter intake (in kg bull^{-1} d^{-1})
s coefficient (s = -0.141 kg bull^{-1} d^{-1})
x_{rough} share of roughage in feed (in kg kg^{-1})
u coefficient (u = 0.248 kg bull^{-1} d^{-1})
$x_{\mathrm{DM,\,rough}}$ dry matter content of roughage (in kg kg^{-1})
v coefficient (v = 0.014 d^{-1})
w_{BB} mean live weight of a beef bull (in kg bull^{-1})

The bulls described in this work drink 9.5 m^3 bull^{-1} water during their lifespan.

2.9.2.5 Drinking water of the herd and water losses

The overall amount of water required by the herd includes losses by spillage. KTBL (2104) recommends assuming a spillage of 10 %.

$$M_{\mathrm{Wt}} = \left(M_{\mathrm{Wt,\,DC}} \cdot n_{\mathrm{DC}} + M_{\mathrm{Wt,\,calf}} \cdot n_{\mathrm{calf}} + M_{\mathrm{Wt,\,He}} \cdot \left(n_{\mathrm{DH}} + n_{\mathrm{BH}}\right) + M_{\mathrm{Wt,\,BB}} \cdot n_{\mathrm{BB}}\right) \cdot \left(1 + x_{\mathrm{spilt,\,Wt}}\right) \tag{63}$$

where

M_{Wt} overall water required by the herd (in m^3 herd^{-1} lactation^{-1})
$M_{\mathrm{Wt,\,DC}}$ mean amount of drinking water required by a dairy cow (in m^3 cow^{-1} lactation^{-1}) [11]
n_{DC} number of dairy cows in the herd in a given lactation (in cow herd^{-1})
$M_{\mathrm{Wt,\,calf}}$ drinking water required by a calf (in m^3 calf^{-1})
n_{calf} number of calves fed (in calf herd^{-1} lactation^{-1})
$M_{\mathrm{Wt,\,He}}$ drinking water required by a heifer (in m^3 heifer^{-1})
n_{DH} number of dairy heifers fed (in heifer herd^{-1} lactation^{-1})
n_{BH} number of beef heifers fed (in heifer herd^{-1} lactation^{-1})
$M_{\mathrm{Wt,\,BB}}$ drinking water required by a beef bull (in m^3 bull^{-1})
n_{BB} number of beef bulls fed (in bull herd^{-1} lactation^{-1})
$x_{\mathrm{spilt,\,Wt}}$ losses by spillage ($x_{\mathrm{spilt,\,Wt}}$ = 0.1 kg kg^{-1})

2.9.2.6 Process water requirements of dairy cows

Process water is required to clean the building and the milking installations. A 100-cow unit needs 10 milking machines (KTBL, 2014). For these KTBL (2009) estimates a water consumption of 225 m^3 herd^{-1} a^{-1}. In addition, water is used to clean and disinfect the house. Assuming an area per cow of 7.77 m^2 cow^{-1} (KTBL, 2014) and a water volume of 20 l m^{-2} a^{-1}, a total of 15.5 m^3 herd^{-1} a^{-1} can be determined.

This work assumes overall process water requirements of 240 m^3 herd^{-1} a^{-1}.

2.9.2.7 Process water requirements of heifers and beef bulls

One single cleaning of the livestock building per production cycle is assumed in accordance with KTBL (2014). With areas of 10 m^2 heifer^{-1} for dairy heifers and 5.4 m^2 animal^{-1} for beef heifers and bulls and 20 l m^{-2} for cleaning once in an animal's lifespan, process water requirements are 200 l animal^{-1} for a dairy heifer and 108 l animal^{-1} for beef heifers and bulls.

2.9.2.8 Water requirements in plant production

KTBL (2014) suggests that each measure of crop protection requires 300 l ha^{-1} water. The number of applications for the crops under consideration is listed in Table A3.

2.9.2.9 Water requirements in sugar production

Sugar beets contain so much water that the process of sugar production does not need extra water. However, water in the cooling cycle has to be replaced. The amounts are of minor importance and neglected in this work (Südzucker, 2014a).

2.9.2.10 Electric energy requirements of water production

According to ATT et al. (2011) the provision of 1 m^3 of drinking water in Germany requires 0.51 kWh. We assume that all water dealt with in this work is drinking water from the public water-supply.

[11] Our calculations in Dämmgen et al. (2016a) differentiate between cows in different lactations.

2.9.3 CO_2-equivalents for the provision of electrical energy

The latest estimates of the GHG emissions connected to the generation of electricity using the German mix of primary fuels yielded 0.595 kg kWh^{-1} CO_2-eq (Icha, 2014).

2.9.4 CO_2-equivalents for the provision of diesel fuel and natural gas

For diesel fuel, IFEU (2012) determined GHG emissions from the diesel production chain to be 9944 kg TJ^{-1} CO_2-eq. With a calorific value of 42.96 MJ (kg diesel)$^{-1}$, GHG emissions of 0.427 kg (kg diesel)$^{-1}$ CO_2-eq or 0.355 kg (l diesel)$^{-1}$ CO_2-eq (density of diesel fuel 0.832 kg l^{-1}) were obtained.

For natural gas, Fritsche (2003) calculated that the mean GHG emissions from the provision of CH_4 sold on the German markets in 2000 amounted to 35.2 g kWh^{-1}.

2.10 Indirect nitrous oxide emissions

N_2O emissions originate from N inputs other than intentional fertilizing or as unintentional results of agricultural N inputs from N transformation in soils or water bodies, such as:

- the atmospheric deposition of gaseous NH_3 and NO_2 as well as particulate NH_4-N and NO_3-N,
- the transformation of N species in water bodies after surface run-off or leaching.

If agricultural sources contribute to these inputs, the emissions have to be accounted for as indirect agricultural emission.

IPCC (2006b) give calculation procedures for both subsets (Equations (64) and (65)). In contrast to national emission inventory calculations, we attribute the respective emissions from fertilizer production, water supply and electricity generation to agriculture as well.

$$E_{\text{N2O, AD}} = \begin{bmatrix} \left(E_{\text{NH3-N, MaM}} + E_{\text{NO-N, MaM}}\right) \\ + \left(E_{\text{NH3-N, graz}} + E_{\text{NO-N, graz}}\right) \\ + \left(E_{\text{NH3-N, MF}} + E_{\text{NO-N, MF}}\right) \\ + \left(E_{\text{NH3-N, MP}} + E_{\text{NO-N, MP}}\right) \\ + \left(E_{\text{NH3-N, DE}} + E_{\text{NO-N, DE}}\right) \end{bmatrix} \cdot EF_{\text{N2O, AD}} \cdot \gamma_{\text{N2O}} \quad (64)$$

where

$E_{\text{N2O, AD}}$ indirect N_2O emissions from atmospheric deposition (in kg herd^{-1} lactation^{-1})
$E_{\text{NH3-N, MaM}}$ NH_3-N emissions from manure management (in kg herd^{-1} lactation^{-1})
$E_{\text{NO-N, MaM}}$ NO-N emissions from manure management (in kg herd^{-1} lactation^{-1})
$E_{\text{NH3-N, graz}}$ NH_3-N emissions during grazing (in kg herd^{-1} lactation^{-1})
$E_{\text{NO-N, graz}}$ NO-N emissions during grazing (in kg herd^{-1} lactation^{-1})
$E_{\text{NH3-N, MF}}$ NH_3-N emissions from application of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\text{NO-N, MF}}$ NO-N emissions from application of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\text{NH3-N, MP}}$ NH_3-N emissions from the production of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\text{NO-N, MP}}$ NO-N emissions from the production of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\text{NH3-N, DE}}$ NH_3-N emissions from the use of diesel engines and CH_4 fired boilers (in kg herd^{-1} lactation^{-1})
$E_{\text{NO-N, DE}}$ NO-N emissions from the use of diesel engines and CH_4 fired boilers (in kg herd^{-1} lactation^{-1})
$EF_{\text{N2O, AD}}$ emission factor for indirect N_2O from atmospheric depositions ($EF_{\text{N2O, Dep}}$ = 0.010 kg kg^{-1} N)
γ_{N2O} stoichiometric conversion factor (γ_{N2O} = 44/28 kg kg^{-1} kmol kmol^{-1})

$$E_{\text{N2O, leach}} = M_{\text{N, soil}} \cdot x_{\text{leach}} \cdot EF_{\text{N2O, leach}} \cdot \gamma_{\text{N2O}} \quad (65)$$

and:

$$M_{\text{N, soil}} = M_{\text{N, MaM}} + M_{\text{N, graz}} + M_{\text{N, MF}} + M_{\text{N, CR}} \quad (66)$$

where

$E_{\text{N2O, leach}}$ indirect N_2O emission from run-off and leaching (in kg herd^{-1} lactation^{-1})
$M_{\text{N, soil}}$ N available in soil (in kg herd^{-1} lactation^{-1})
x_{leach} fraction of N leached (x_{leach} = 0.30 kg kg^{-1})
$EF_{\text{N2O, leach}}$ emission factor for N_2O from leached N ($EF_{\text{N2O, leach}}$ = 0.0075 kg kg^{-1} N)
γ_{N2O} stoichiometric conversion factor (γ_{N2O} = 44/28 kg kg^{-1} kmol kmol^{-1})
$M_{\text{N, MaM}}$ N input into soil from manure management (in kg herd^{-1} lactation^{-1})
$M_{\text{N, graz}}$ N input into soil during grazing (in kg herd^{-1} lactation^{-1})
$M_{\text{N, MF}}$ N input into soil with mineral fertilizers (in kg herd^{-1} lactation^{-1})
$M_{\text{N, CR}}$ N input into soil from crop residues (in kg herd^{-1} lactation^{-1})

2.11 Production characteristics (indicators)

2.11.1 Nitrogen balance

The area related N balance quantifies and helps to analyse the potential N surplus. OECD (2001) defines this indicator („surface nitrogen balance indicator") as the area related difference between N inputs into the system and N outputs. Our work uses the entire N from manure management for plant production. It also takes account of areas for seed production. Hence, the methodology given in OECD (2001) is reduced to Equation (67).

$$M_{\text{A, diff}} = \frac{\left(M_{\text{N, MF}} + M_{\text{N, Leg}} + M_{\text{N, AD}}\right) - \left(M_{\text{N, milk}} + M_{\text{N, car}}\right)}{A_{\text{cropped}}} \quad (67)$$

where

$M_{\text{A, diff}}$ area related N mass difference of inputs and outputs (in kg ha^{-1})
$M_{\text{N, MF}}$ mineral fertilizer N applied (in kg herd^{-1} lactation^{-1})
$M_{\text{N, Leg}}$ N fixed by legumes (in kg herd^{-1} lactation^{-1})

$M_{N, AD}$ N input with atmospheric deposition (in kg herd^{-1} lactation^{-1})
$M_{N, milk}$ N output with milk (in kg herd^{-1} lactation^{-1})
$M_{N, car}$ N output with carcasses (in kg herd^{-1} lactation^{-1})
$A_{cropped}$ cropped area (in ha herd^{-1} lactation^{-1})

2.11.2 Nitrogen efficiency

Nitrogen efficiency is defined as the fraction of N used in products and the overall amount of N in inputs to the system. OECD (2001) uses the indicator "efficiency of nitrogen use in agriculture" to characterize resource protection and environmental compatibility in agricultural production.

$$\eta_N = \frac{M_{N, milk} + M_{N, car}}{M_{N, MF} + M_{N, Leg} + M_{N, AD}} \quad (68)$$

where
η_N nitrogen efficiency (in kg kg^{-1})
$M_{N, milk}$ N output with milk (in kg herd^{-1} lactation^{-1})
$M_{N, car}$ N output with livestock carcasses (in kg herd^{-1} lactation^{-1})
$M_{N, MF}$ N input with mineral fertilizers (in kg herd^{-1} lactation^{-1})
$M_{N, Leg}$ N fixed by legumes (in kg herd^{-1} lactation^{-1})
$M_{N, AD}$ N input with atmospheric deposition (in kg herd^{-1} lactation^{-1})

2.11.3 Allocation of emissions to milk and meat protein production

Production of milk and meat is linked by nature and cannot be separated. Keeping in mind the goal of this work, a formal separation of total emissions can be based on the respective amounts of protein produced:

$$E_{X, milk} = E_{X, total} \cdot \frac{XP_{milk}}{XP_{total}} \quad \ldots\ldots\ldots\ldots \quad E_{X, meat} = E_{X, total} \cdot \frac{XP_{meat}}{XP_{total}} \quad (69)$$

where
$E_{X, milk}$ share of a trace gas X attributed to milk production (in kg herd^{-1} lactation^{-1})
$E_{X, total}$ overall emissions of a trace gas X (in kg herd^{-1} lactation^{-1})
XP_{milk} amount of protein in milk sold (in kg herd^{-1} lactation^{-1})
XP_{Mtotal} amount of protein sold with milk and carcasses (in kg herd^{-1} lactation^{-1})
$E_{X, meat}$ share of a trace gas X attributed to meat production (in kg herd^{-1} lactation^{-1})
XP_{meat} amount of protein in carcasses sold (in kg herd^{-1} lactation^{-1})

3 Discussion

3.1 Limits of calculations – comparisons with other published methodologies

This work limits itself to mass flows. The determination of social and monetary characteristics or indicators (see Thomet and Durgiai, 2008) is not dealt with. However, our work aims at a comprehensive approach, which exceeds the (usual) treatment of the animals and their performance. It allows for the determination of ecological characteristics for the coupled processes of milk and meat production.

Our work is restricted to Holstein populations and Northern Germany with high milk yields. In contrast, Simmental herds are dual purpose herds with different characteristics. Our results may be transferable to other breeds and regions in principle only.

It was not the goal of our work to establish CO_2 footprints, but to describe relevant mass flows in the production system "dairy herd". This is a considerable expansion of the system's limits as compared with Hirschfeld et al. (2008), Frank et al. (2013 a, b) or Müller-Lindenlauf et al. (2014). It implies, however, that comparison of the results is hardly possible.

Our work is much more detailed than Gerber et al. (2010) and covers high-yield herds only. As milk and meat production are treated as a unit, the results of our work cannot be compared directly with Flysjö (2012), Thoma et al. (2013) or Vergé et al. (2013).

Comparisons with data from other investigations are possible albeit limited. Their results will be discussed with ours in Dämmgen et al. (2016a, b).

3.2 Uncertainties

Our calculation procedures make intensive use of the methodologies applied in national emission reporting. Here, uncertainties have to be addressed and communicated. Haenel et al. (2016) report that the German inventory's uncertainties for GHG are 37.4 % (mainly due to uncertainties of N_2O emissions), and about 17.3 % for NH_3.

One final goal of our work is the comparison of scenarios with different N inputs as well as livestock losses and illnesses. The relative differences between the results obtained for the scenarios are likely to be smaller than the absolute differences.

Appendices

Appendix 1
Productive lifespans, yield depressions due to illnesses and non-marketable milk

A1.1 Productive lifespans

The data for the work at hand reflect the situation in Northern Germany where Holsteins are the predominant breed.

The mean numbers of lactations observed is given in Table A1.

Table A1
Productive lifespans of dairy cows in North German federal states (VIT, 2014)

region	number of cows evaluated	productive lifespan	
		months	lactations
Niedersachsen	200337	37.3	2.70
Hessen	37867	36.0	2.61
Mecklenburg-Vorpommern	55134	34.3	2.48
Sachsen-Anhalt	38931	34.4	2.49
Brandenburg	49898	33.2	2.40

Productive lifespans in the Mecklenburg-Vorpommern farms investigated by Harms (undated b) varied considerably – between 2 and 7.7 years.

It is obvious that the figures for productive lifespans in months and lactations do not match the information on losses given in Table 1 at first sight. With losses as in Table 1, lifespans as in Table A1 can only be achieved if additional heifers are bought. Harms (undated b) refers to this practice. The use of sexed semen is another option. Here, the additional advantage is the reduction of the number of stillborn calves at first calving (that are mainly male) (Detterer and Meinecke-Tillmann, 2011).

A1.2 Performance depression and non-marketable milk

As a rule, illnesses of dairy cows cause milk yield depressions. In addition, the share of milk contaminated with pathogens or medicine and its metabolites cannot be sold and must be discharged. (For further details see Appendix 2.)

Table A2
Incidences of illnesses that result in yield depression and non-marketable milk

source	illness	frequency animal animal^{-1}	remarks
Østergaard and Gröhn (1999)	mastitis afterbirth retention milk fever abomasum displacement	0.486 0.092 0.003 0.002	different breeds under research farm conditions
Fleischer et al. (2001)	mastitis afterbirth retention milk fever abomasum displacement foot lesions	0.257 0.099 0.101 0.013 0.231	single illnesses are considered independent of one another
Wilson et al. (2004)	mastitis afterbirth retention milk fever abomasum displacement lameness	0.241 0.106 0.035 0.026 0.317	2 herds with regular bST treatment *
Krömker and Pfannenschmidt (2005)	mastitis	0.452	organic farming
Stock et al. (2014)	mastitis afterbirth retention milk fever abomasum displacement	0.476 0.104 0.047 0.026	early and late occurrences during a lactation
Zoche and Spilke (2012)	mastitis	0.362	weighted mean
Rudolphi et al. (2012)	share of all illnesses within 10 d p.p.	0.481 (lac_1**) 0.376 (lac_2) 0.420 (lac_3) 0.544 ($\geq lac_4$)	77.1 % and 71.3 % of all cows and heifers, resp., needed at least 1 treatment. 88.1 % of cows after 4th lactation became ill.
	share of all illnesses between days 11 and 30 p.p.	0.178 (lac_1) 0.196 (lac_2) 0.198 (lac_3) 0.164 ($\geq lac_4$)	Illnesses comprised
	share of all illnesses between days 31 and 100 p.p.	0.162 (lac_1) 0.220 (lac_2) 0.201 (lac_3) 0.159 ($\geq lac_4$)	fertility problems: 42.8 %; foot and limbs lesions: 35.1 %; mastitis: 32.2 %; metabolism: 13.5 %
	share of all illnesses after day 100 p.p.	0.179 (lac_1) 0.208 (lac_2) 0.181 (lac_3) 0.133($\geq lac_4$)	dystocia 4.7 % mean frequency off illnesses per cow: 2.8

* bST: bovine somatotropin;
** lac1: 1st lactation, etc.

Table A3
Parameters characterizing milk yield depression due to diseases (overall number of cases) as function of the number of lactations (after Rudolphi et al., 2012)

number of lactation	absolute (weighted) milk yield depression	mean milk yield of healthy cows	relative yield depression	frequency of illnesses
	kg cow^{-1} lactation^{-1}	kg cow^{-1} lactation^{-1}	kg kg^{-1}	cow cow^{-1}
1st	-125*	9025	0.0139	0.713
2nd	-356*	10648	0.0334	0.771**
3rd	-345*	10948	0.0315	0.771**
≥ 4th	-319*	10823	0.0295	0.881

* weighted mean obtained from differentiated incidences in various periods of lactations and related depressions ** means given in Rudolphi et al. (2012)

Table A4
Estimate of milk losses (amounts of non-marketable milk) due to presence of pathogens or medicine or its metabolites

number of lactation	absolute yield depression per mastitis infection	share of cows with treatments potentially causing milk to be discharged	amount of non-marketable milk	mean milk yield of healthy cows	fraction of milk to be discharged
	kg cow^{-1} lactation^{-1}	%	kg cow^{-1} lactation^{-1}	kg cow^{-1} lactation^{-1}	kg kg^{-1}
1st	287*	35.7**	102	9025	0.0113
2nd	287*	38.6**	111	10648	0.0104
3rd	287*	38.6**	111	10948	0.0101
≥ 4th	287*	44.1**	127	10823	0.0117

* according to Rudolphi et al. (2012) for clinical treatment of mastitis;
** assuming half of all treatments in the respective lactation (see Table A3)

The results of a survey of incidences are compiled in Table A2. These incidences have to be combined with typical yield depression data and with information on non-marketable milk.

Rudolphi et al. (2012) give detailed information on all first illnesses and the affiliated yield depressions of sick cows in comparison with healthy cows. From these data we were able to deduce Table A3.

No information is yet available on the share of milk that has to be discharged. Therefore we assume for the time being that half of the incidences cause non-marketable milk. The yield depression observed for mastitis (287 kg cow^{-1} lactation^{-1}) is related to the milk yield of healthy cows. The results are shown in Table A4.

Non-marketable milk primarily results from the treatment of mastitis infections with antibiotics. As a rule, treatments last for about five days. We use the absolute milk depression to quantify the amount of non-marketable milk assuming that 50 % of all illnesses (Table A3) need to be treated in this way. Hence the amount of non-marketable milk (that has to be discharged) for the data provided in Table A4 is:

$$\Delta y_{\text{milk, dis, n}} = m_{\text{milk, depr}} \cdot \frac{1}{2} \cdot I_{\text{sick, n}} \qquad \text{(A1)}$$

where

$\Delta y_{\text{milk, dis, n}}$ amount of milk discharged in n-th lactation (in kg cow^{-1} lactation^{-1})

$m_{\text{milk, depr}}$ absolute milk depression per mastitis infection (in kg cow^{-1} lactation^{-1})

$I_{\text{sick, n}}$ frequency of illnesses n-th lactation (in cow cow^{-1})

The fraction of milk to be discharged is:

$$x_{\text{dis, n}} = \frac{\Delta y_{\text{milk, dis, n}}}{y_{\text{milk, hc}}} \qquad \text{(A2)}$$

where

$x_{\text{dis,, n}}$ fraction of milk that has to be discharged n-th lactation (in kg kg^{-1})

$\Delta y_{\text{milk, dis, n}}$ amount of milk discharged in n-th lactation (in kg cow^{-1} lactation^{-1})

$y_{\text{milk, hc}}$ amount of milk produced by a healthy cow (in kg cow^{-1} lactation^{-1})

Appendix 2
Fate of discharged milk in the manure management

A2.1 Amounts of discharged milk

The amount of milk to be discharged per herd is:

$$\Delta Y_{\text{milk, dis, n}} = Y_{\text{milk, n}} \cdot \frac{1}{2} \cdot I_{\text{sick, n}} \cdot x_{\text{dis, n}} \qquad \text{(A3)}$$

where

$\Delta Y_{milk, dis, n}$ amount of milk discharged in n-th lactation (in Mg herd^{-1} lactation^{-1})
$Y_{milk, n}$ milk yield in n-th lactation (in Mg herd^{-1} lactation^{-1})
$I_{sick, n}$ frequency of illnesses n-th lactation (in cow cow^{-1})
$x_{dis,, n}$ fraction of milk that has to be discharged n-th lactation (in kg kg^{-1})

A2.2 CH_4 emissions from manure management of discharged milk

The amount of CH_4 released from storage is estimates in accordance with IPCC (2006b) as follows:

$$E_{CH4, herd, milk} = VS_{milk, dis} \cdot B_o \cdot \rho_{CH4} \cdot MCF \qquad (A4)$$

where

$E_{CH4, herd, milk}$ CH_4 emission from storage caused by discharged milk (in Mg herd^{-1} lactation^{-1} CH_4)
$VS_{milk, dis}$ organic matter (VS) input with discharged milk (in Mg herd^{-1} lactation^{-1})
B_o maximum CH_4 producing capacity (B_o = 0.24 m^3 CH_4 (kg VS)$^{-1}$
ρ_{CH4} density of CH_4 under standard conditions (ρ_{CH4} = 0.67 kg m^{-3})
MCF CH_4 conversion factor for storage tanks with natural crust (MCF = 0.1 m^3 m^{-3})

and

$$VS_{milk, dis, n} = Y_{milk, n} \cdot \frac{1}{2} \cdot I_{sick, n} \cdot x_{dis, n} \cdot x_{DM, milk} \cdot (1 - x_{ash, milk}) \qquad (A5)$$

where

$VS_{milk, dis, n}$ VS input with discharged milk in n-th lactation (in Mg herd^{-1} lactation^{-1})
$Y_{milk, n}$ milk yield in n-th lactation (in Mg herd^{-1} lactation^{-1})
$I_{sick, n}$ incidence of illnesses in n-th lactation (in cow cow^{-1})
$x_{v. n}$ fraction of discharged milk in n-th lactation (in kg kg^{-1})
$x_{DM, milk}$ dry matter content of full-cream milk, 0.04 kg kg^{-1} fat ($x_{DM, milk}$ = 0.132 kg kg^{-1})
$x_{ash, milk}$ ash content of full-cream milk, 0.04 kg kg^{-1} fat ($x_{ash, milk}$ = 0.055 kg kg^{-1})

B_o is depending on the substrate fermented. No information could yet be found for milk. The value for cattle slurry was used instead.

A2.3 Amounts of N in discharged milk

The amount of N in milk protein discharged into the slurry store is:

$$M_{N, milk, dis} = m_{milk, dis} \cdot \left(x_{CP, milk, 1} + (t_{util} - t_1) \cdot x_{CP, milk, 2}\right) \cdot \frac{1}{t_{util}} \cdot x_{N, CP, milk} \qquad (A6)$$

where

$M_{N, milk, dis}$ amount of N in discharged milk (in Mg herd^{-1} lactation^{-1})
$m_{milk, dis}$ amount of discharged milk (in Mg herd^{-1} lactation^{-1})

Table A5
Silage making - overall, on field and ensiling losses

losses and feeds	process	DM losses %	source
overall losses			
grass silage		20	Bastiman and Altman (1985)
grass silage		15	Heilmann et al. (2003)
on field losses			
green fodder		2 to 18	Weissbach (1993)
		11 and 4	Gordon et al. (1961)
grass silages		5.3 to 21.6 *	van Schooten and Philipsen (2012)
ensiling losses			
green fodder	during fermentation	5 to 16	Weissbach (1993)
	silage juice	0 to 10	Weissbach (1993)
	cutting	1 to 30	Weissbach (1993)
grass silages		9	Köhler et al. (2013a)
	„invisible loss“	15 to 25	McGechan (1990)
	during fermentation	7.3 to 24.9	van Schooten and Philipsen (2012)
maize silages		10	Köhler et al. (2013a)
		8.1	Pahlow et al. (2003)
removal, cutting			
green fodder	cutting	1 to 6	Weissbach (1993)
grass silages		9	Bastiman and Altman (1985)
		3.0 to 15.8	van Schooten and Philipsen (2012)

* data from practicing farms

$x_{CP, milk, 1}$ crude protein content of full-cream milk in 1st lactation ($x_{CP, milk, 1}$ = 0.0333 kg kg^{-1})
t_{util} productive lifespan of a cow (in lactation)
t_1 duration of 1st lactation (in lactation)
$x_{CP, milk, 2}$ crude protein content of full-cream milk in subsequent lactations ($x_{CP, milk, 2}$ = 0.0330 kg kg^{-1})
$x_{N, CP, milk}$ N content of milk protein ($x_{N, CP, milk}$ = 1/6.38 kg kg^{-1})

The determination of NH_3 emissions from storage and application presupposes the knowledge of the relevant TAN content.

$$M_{TAN, milk, dis} = M_{N, milk, dis} \cdot x_{min, milk} \quad (A7)$$

$$M_{Norg, milk, dis} = M_{N, milk, dis} \cdot (1 - x_{min, milk}) \quad (A8)$$

where
$M_{TAN, milk, dis}$ amount of TAN in discharged milk (in Mg herd^{-1} lactation^{-1})
$M_{N, milk, dis}$ amount of N in discharged milk (in Mg herd^{-1} lactation^{-1})
$x_{min, milk}$ fraction of N mineralized in storage N (in kg kg^{-1})
$M_{Norg, milk, dis}$ amount of organic N in discharged milk (in Mg herd^{-1} lactation^{-1})
etc.

As reliable data is missing, our preliminary assumption is that half of the organic N will be mineralized.

The emissions during storage, application and incorporation are calculated using the same methodology and constants as for cattle slurry (Chapter 2.4.2).

Appendix 3 Conservation losses

A3.1 Amounts of losses

Conservation of feed by ensiling or haymaking is connected with dry matter losses. Due to the large amounts of silage produced this item receives special attention. Table A5 collates our findings for total losses and losses for single steps in the process.

Table A6
Dry matter losses during ensiling of green fodder as clamp silage

losses		good	handling bad	chosen
		% DM	% DM	% DM
fermentation	30 % DM	5	10	8
silage juice	30 % DM	0	0	0
exclusion of air	sufficient	5	5	5
removal		1	6	4
total		11	21	17

The data in Table A5 differ greatly. KTBL (2009) summarized the findings of Weissbach (1993) as in Table A6 where they differentiate between good and bad handling.

Silage that was exposed to air can no longer be used as feed and has to be discharged. This work assumes losses from removal to be 9 % of the original dry matter (total of losses from air infiltration and removal).

A3.2 Amounts and fate of discharged silage

The amount of losses to be addressed is:

$$m_{j, dis} = A_{j, sil} \cdot Y_j \cdot x_{j, dis} \quad (A9)$$

where
$m_{j, dis}$ amount of matter lost during removal of an ensiled crop j (in Mg herd^{-1} lactation^{-1})
$A_{j, sil}$ area cultivated for crop j prior to ensiling (in ha herd^{-1} lactation^{-1})
Y_j yield of a crop j (in Mg ha^{-1})
$x_{j, dis}$ fraction lost during ensiling of crop j (in kg kg^{-1})

Discharged silage is removed from the silo and treated in the same way as solid manure. The amount of N in the discharged silage is assumed to be similar to the N content in the respective utilized silage.

$$M_{N, dis, j} = m_{dis, j} \cdot x_{N, sil, j} \quad (A10)$$

where
$M_{N, dis, j}$ N in discharged silage from a crop j (in Mg herd^{-1} lactation^{-1})
$m_{dis, j}$ mass of discharged silage from a crop j (in Mg herd^{-1} lactation^{-1})
$x_{N, sil, j}$ N content of silage from a crop j (in kg kg^{-1})

Silage is acid. Köhler et al. (2013b) give mean pH values for grass silage and maize silage of 4.4 and 3.9, respectively. Therefore, NH_3 losses can be excluded if the storage time is adequate. For N_2O, NO und N_2 losses the emission factors for solid manure are applied until further information is available (IPCC, 2006b; Haenel et al., 2016):

$EF_{N2O-N, sm}$ 0.005 kg kg^{-1}
$EF_{NO-N, sm}$ 0.0005 kg kg^{-1}
$EF_{N2, sm}$ 0.015 kg kg^{-1}

These are used to quantify N inputs into soils:

$$M_{soil, dis, j} = M_{N, j, dis} \cdot \left(1 - \left(EF_{N2O-N, sm} + EF_{NO-N, sm} + EF_{N2, sm}\right)\right) \quad (A11)$$

where
$M_{soil, dis j}$ N input into soils from discharged silage losses of crop j (in kg herd^{-1} lactation^{-1})
$M_{N, dis, j}$ N in discharged losses of ensiled crop j (in Mg herd^{-1} lactation^{-1})

$EF_{N2O-N, sm}$ emission factor for N_2O, solid manure storage (in kg kg^{-1})
$EF_{NO-N, sm}$ emission factor for NO, solid manure storage (in kg kg^{-1})
$EF_{N2, sm}$ emission factor for N_2, solid manure storage (in kg kg^{-1})

Direct emissions are calculated from soil inputs as in Chapter 2.10. These amounts are negligible and not accounted for in the N balance.

Appendix 4
Determination of cow numbers at the beginning and the end of a lactation

Loss rates for cows in two lactation periods n and n+1 with animal number N_n and N_{n+1} are $x_{loss, n}$ and $x_{loss, n+1}$. Figure A1 is used to illustrate the calculation procedure to establish a set of animal numbers such as in Tables 2 and 3:

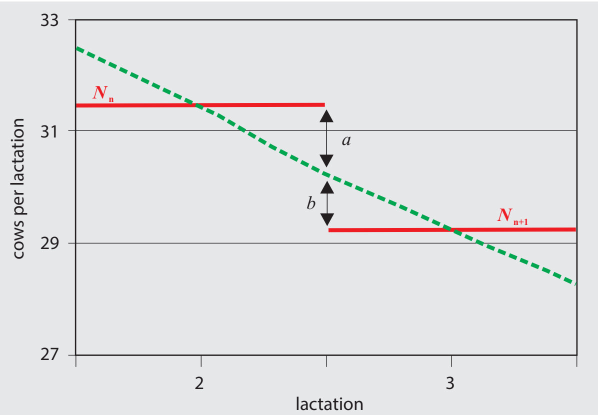

Figure A1
Model describing the number of cows at the beginning and the end of two consecutive lactations

It is assumed that:

$$a = N_n \cdot y_n$$
$$b = N_{n+1} \cdot y_{n+1}$$
$$a + b = N_n - N_{n+1}$$

where
a difference between number of cows at the begin of lactation n+1, N_{n+1}, and the mean animal number in lactation n, N_n (in cow $herd^{-1}$ $lactation^{-1}$)
N_n mean number of cows in lactation n (in cow $herd^{-1}$ $lactation^{-1}$)
y_n factor describing losses during lactation n
etc.

This results in:

$$b = \frac{N_n \cdot y_n}{1 + \frac{N_n \cdot y_n}{N_{n+1} \cdot y_{n+1}}}$$

and:

$$a = (N_n - N_{n+1}) - b$$

where
b difference between number of cows *at the beginning* of lactation n+1, $N_{n+1 B}$, and the *mean* animal number in lactation n+1, N_{n+1} (in cow $herd^{-1}$ $lactation^{-1}$)
N_n mean number of cows in lactation n+1 (in cow $herd^{-1}$ $lactation^{-1}$)
y_{n+1} loss rate in lactation n+1 (in cow cow^{-1})
etc.

In the example presented, values for a and b are 1.22 and 1.00 cow $herd^{-1}$ $lactation^{-1}$.

The application of this procedure to describe the numbers at the end of the 1st lactation yields larger numbers than its application to the 2nd lactation. However, the application of this procedure for the description of 1st lactation yields numbers for the beginning of the 2nd lactation that differ slightly from the results obtained with the above calculations. The differences are considered negligible.

The number of cows at the end of the lactation obeys:

$$N_{1,B} = N_1 + (N_1 - N_2) - a_1 = 2N_1 - N_2 - b_1$$

where
$N_{1, B}$ number of cows at the beginning of the 1st lactation (in cow $herd^{-1}$ $lactation^{-1}$)
N_1 mean number of cows in lactation 1 (in cow $herd^{-1}$ $lactation^{-1}$)
N_2 mean number of cows in lactation 2 (in cow $herd^{-1}$ $lactation^{-1}$)
a_1 difference between the number of cows at the beginning of lactation 2, N_{2B}, and the mean number of lactation 1, N_1 (in cow $herd^{-1}$ $lactation^{-1}$)
b_1 difference between the number of cows at the beginning of lactation 2, N_{2B}, and the mean number of lactation 2, N_2 (in cow $herd^{-1}$ $lactation^{-1}$)

Appendix 5
Allocation factors – additional information

Linseed extraction meal: Linseed contains about 40 % linseed oil. After the extraction procedure with subsequent toasting about 2.5 % of the oil remains in the meal, i.e., 100 % to 37.5 % of the original mass is extracted meal (Ullmann, 1966, vol. 17). Hence, 1 Mg linseed yields 0.629 Mg linseed extraction meal.

Rapeseed extraction meal: Rapeseed contains 40 to 50 % rapeseed oil. After extraction and toasting, about 2.5 % of the oil remains in the extraction meal (Ullmann, 1956, vol. 7). Using a mean oil content of 45 %, then 1 Mg rapeseed yields 0.575 Mg rapeseed extraction meal.

Wheat bran: The mass of the endosperm accounts for about 80 % of the mass of a grain. For bread flour about 74 % of the grain weight is in the flour (Ullmann, 1957, vol. 8). The rest is bran.

Sugar beet shreds: A beet yield of 60.9 Mg ha^{-1} (fresh) and a DM content of 0.175 Mg Mg^{-1} results in a mass of sugar beet shreds of 2.9 Mg ha^{-1}. Related to DM, the mass fraction amounts to 27.7 %. (Expert judgement Brinker)

Sugar beet shreds molasses: From the above mentioned yields 3.9 Mg ha^{-1} (DM) molasses shreds can be obtained. Hence the mass fraction is 37 %. (Expert judgement Brinker)

Molasses: A beet yield as above allows for the production of 2.88 Mg ha^{-1} molasses, i.e. 2.7 % of the amount harvested. (Expert judgement Brinker)

Appendix 6
Nutrient surplus in German agricultural practice

The German fertilizer enactment (Düngeverordnung, DüV; DüV, 2007) gives a methodology to determine amounts of N fertilizer as a function of crop type and expected yield. It also permits a fertilizer surplus of up to 60 kg ha^{-1} a^{-1} N (§ 9). The application of surplus N is obviously common practice in those federal states where Holsteins are kept:

For Niedersachsen and Nordrhein-Westfalen mean surplus N amounted to 58 and 84 kg ha^{-1} a^{-1} for the years 2009 to 2011, respectively (LWK-Nds, 2015; LWK-NRW, 2014). For the same period the German mean surplus was 68 kg ha^{-1} a^{-1}. Kape (2015) reported that in 2010 the surplus calculated for Mecklenburg-Vorpommern was 74.3 kg ha^{-1} a^{-1} without and 86 kg ha^{-1} a^{-1} including atmospheric deposition. The time series given confirms that average surpluses ranged between 60 and 70 kg ha^{-1} a^{-1}. Mehl (2013) pointed out the high spatial variation and reported mean surpluses of more than 80 kg ha^{-1} a^{-1}, deposition not included. An evaluation of Sachsen farms for 2007 to 2009 yielded that 6 farms out of 16 exceeded the 60 kg ha^{-1} a^{-1} limit (at that time not legally binding), and 5 farms exceeded even 80 kg ha^{-1} a^{-1} (Heinitz et al., 2010).

Acknowledgements

The authors received information and help which is gratefully acknowledged, from
Gerhard Brantkatschk, Verband der ölsaatenverarbeitenden Industrie in Deutschland e.V., Berlin
Dr Stefan Brinker, Pfeifer und Langen, Lage,
Dr Heinrich Kleine Klausing, EW Nutrition GmbH, Visbek
Dr Martin Pries, Landwirtschaftskammer Nordrhein-Westfalen, Münster
UD thanks the Leibniz Institute for Farm Animal Livestock Biology for generous support.

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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.

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 milk	slaughtered cows	utilized dairy heifers	slaughtered beef heifers	slaughtered beef bulls	total	share of meat protein %
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

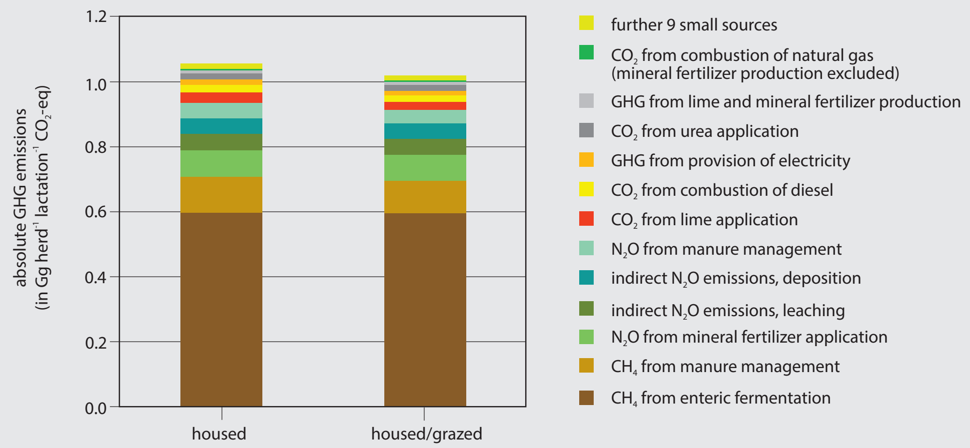

Figure 1

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.

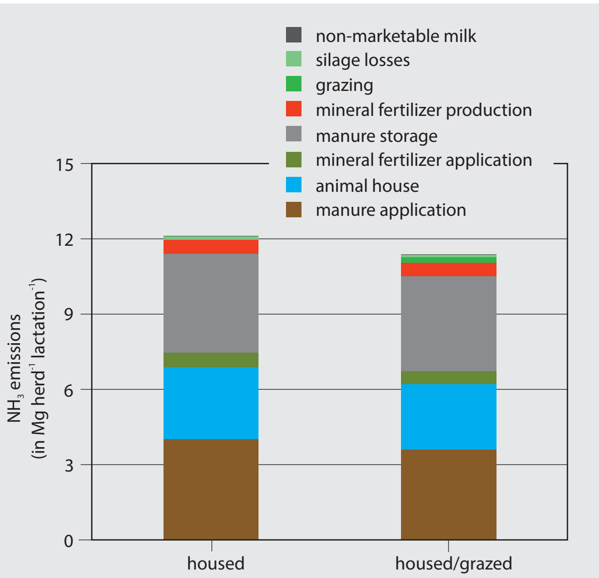

Figure 2
NH_3 emissions from dairy cow herds, nominal milk yield 8000 kg cow^{-1} lactation^{-1} (left bar: no grazing apart from dairy heifers; right bar: all dairy cows grazed 10 h d^{-1} during the vegetation period, in addition)

[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.

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.

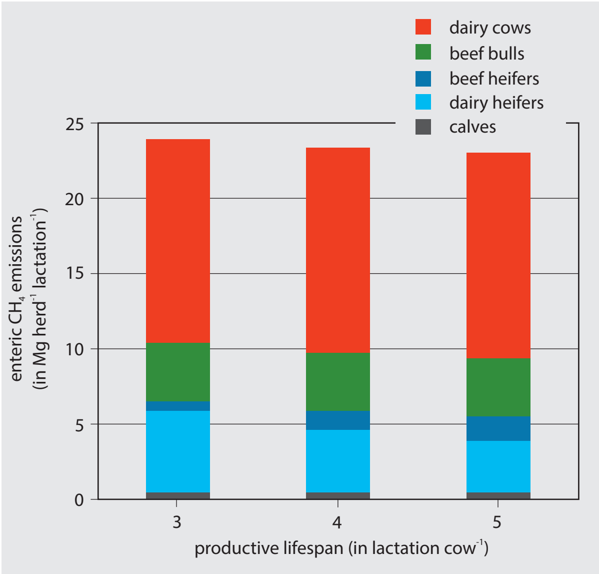

Figure 3
Enteric CH_4 emissions for the respective animal categories, related to the number of lactations per cow (current practice, all other variables as in reference farm, see Table 1)

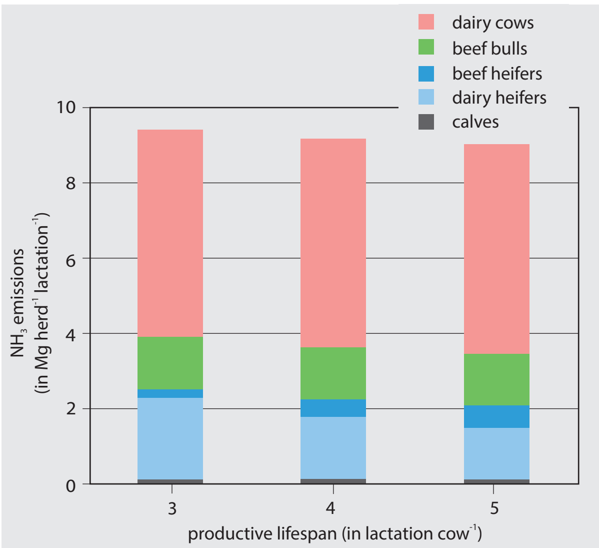

Figure 4
NH_3 emissions of the respective animal categories from manure management (house, storage, application) (current practice, all other variables as in reference farm, see Table 1)

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.

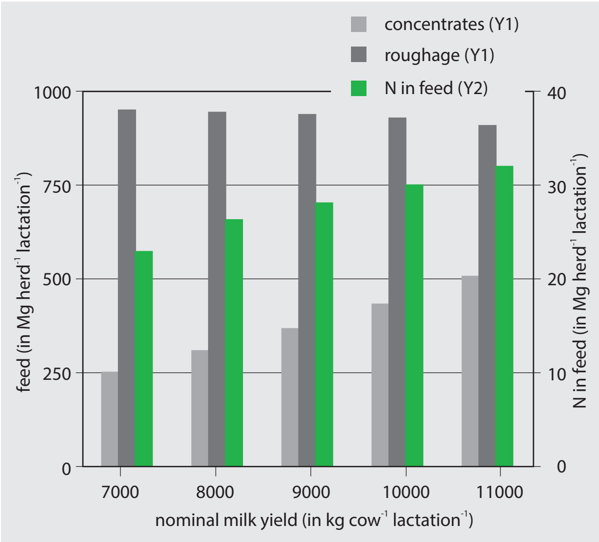

Figure 5
Feed intake of the herds as a function of milk yield. Other variables as in reference farm (see Table 1). Left ordinate: amounts of concentrates and roughage; right ordinate: amounts of N.

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).

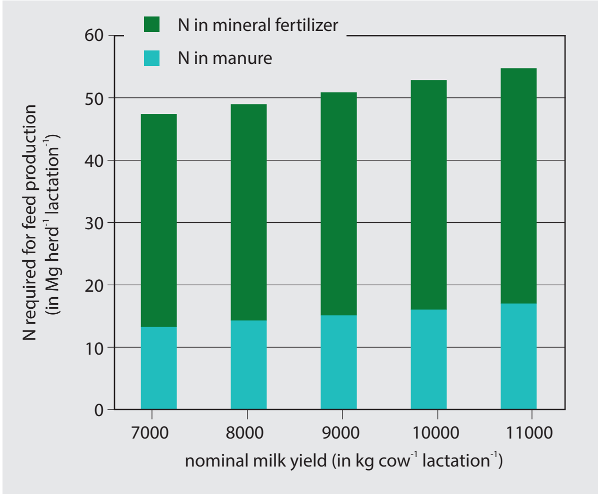

Figure 6
Shares of manure and mineral fertilizer required to meet the N demand of plants as related to milk yields (current practice, all other variables as in reference farm, see Table 1)

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 %).

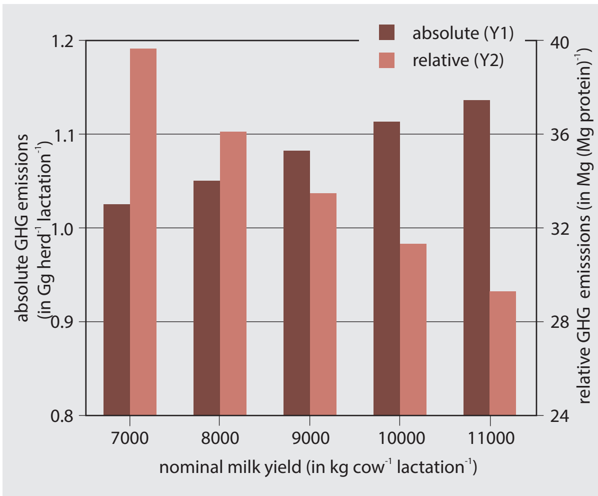

Figure 7
Absolute and protein-related GHG emissions of dairy cow herds as a function of nominal performance (current practice, other variables as for reference farm). Note that axes do not start at origin.

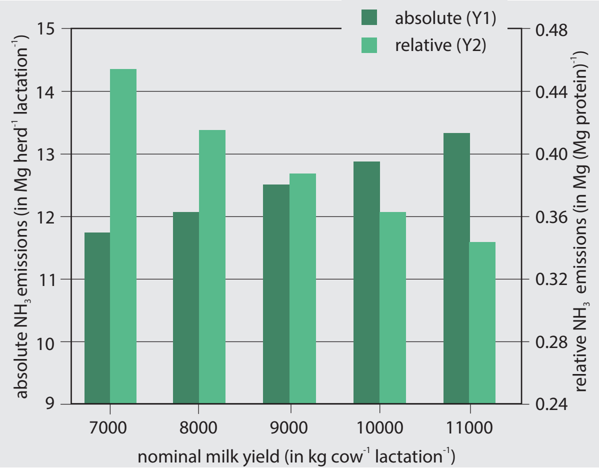

Figure 8

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).

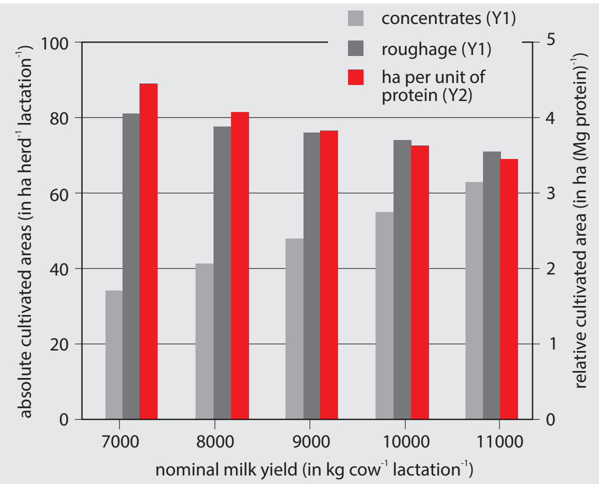

Figure 9

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.

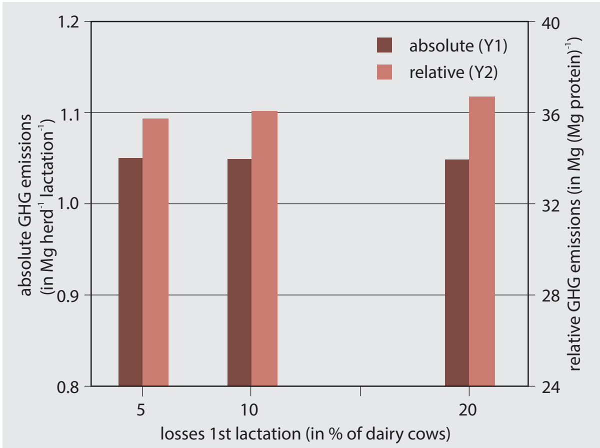

Figure 10

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

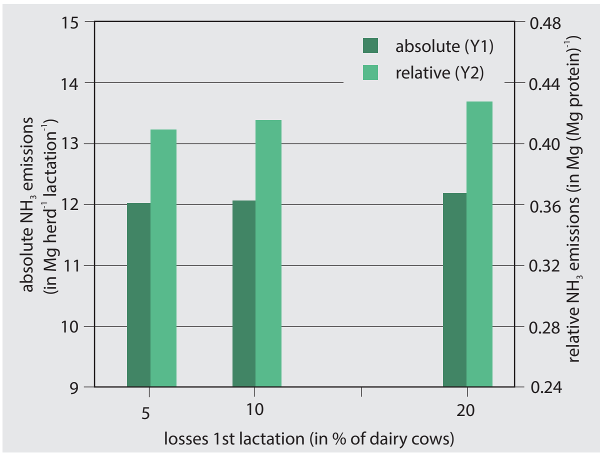

Figure 11

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

[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).

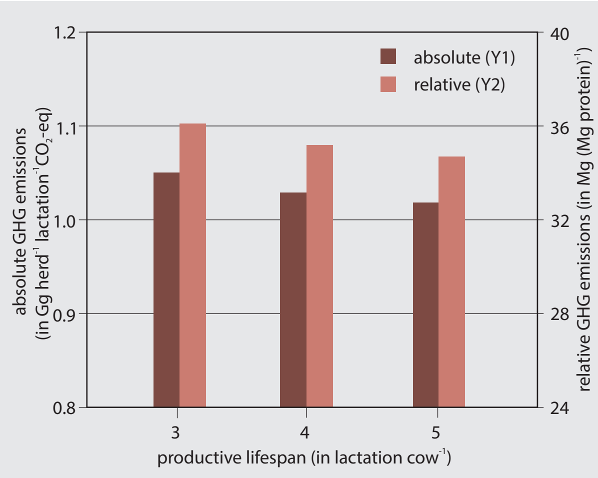

Figure 12
Absolute and protein-related GHG emissions as a function of the useful lifespan of the dairy cows (all other variables as in reference farm)

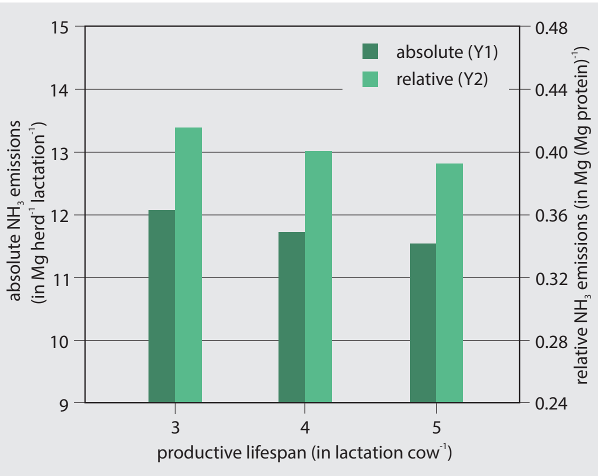

Figure 13
Absolute and protein-related NH_3 emissions as a function of the useful lifespan of the dairy cows (all other variables as in reference farm)

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.

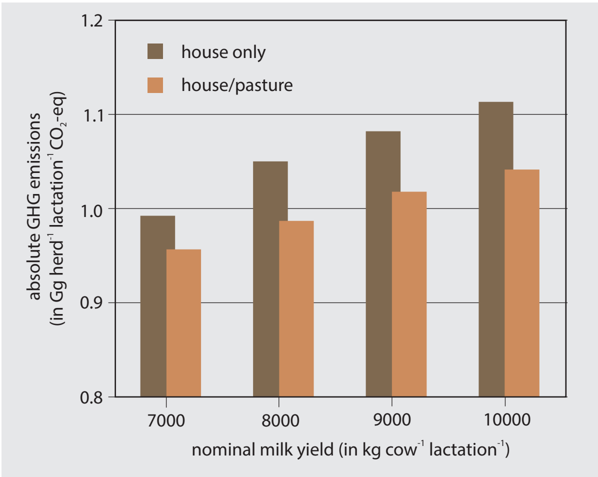

Figure 14
Absolute GHG emissions for the housed herd and for part-time grazing of dairy cows and heifers for varying animal performances (other variables according as in reference farm)

[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.

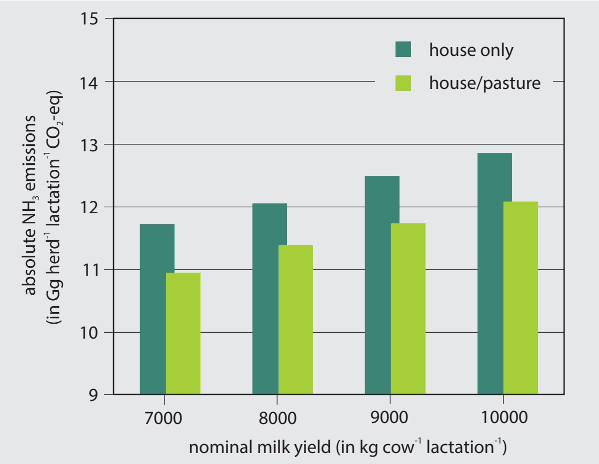

Figure 15
Absolute NH_3 emissions for the housed herd and for part-time grazing of dairy cows and heifers for varying animal performances (other variables as in reference farm)

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.

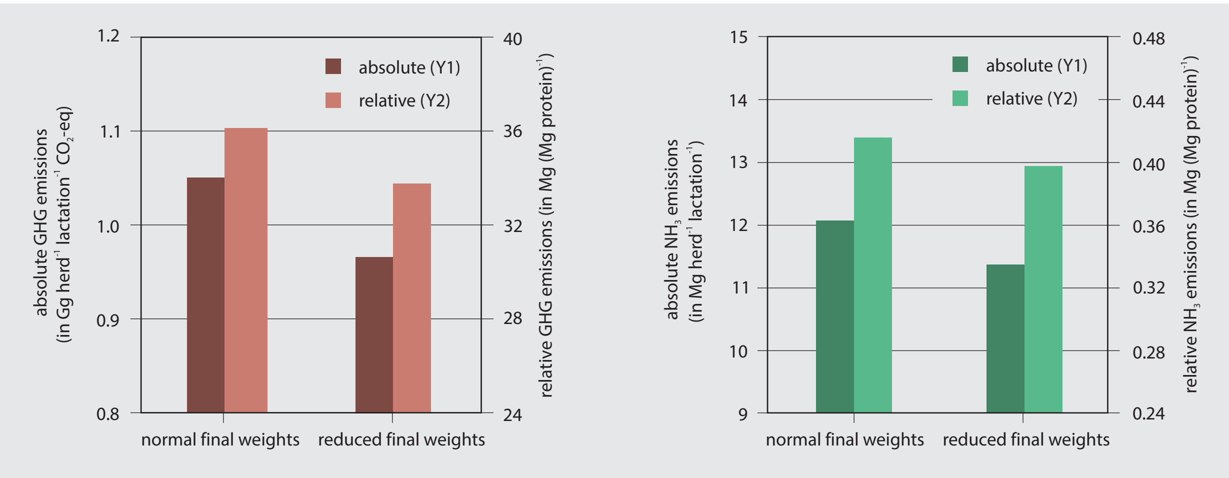

Figure 16
Absolute and protein-related GHG and NH_3 emissions per herd for normal and reduced final live weights (all other variables as in reference farm).

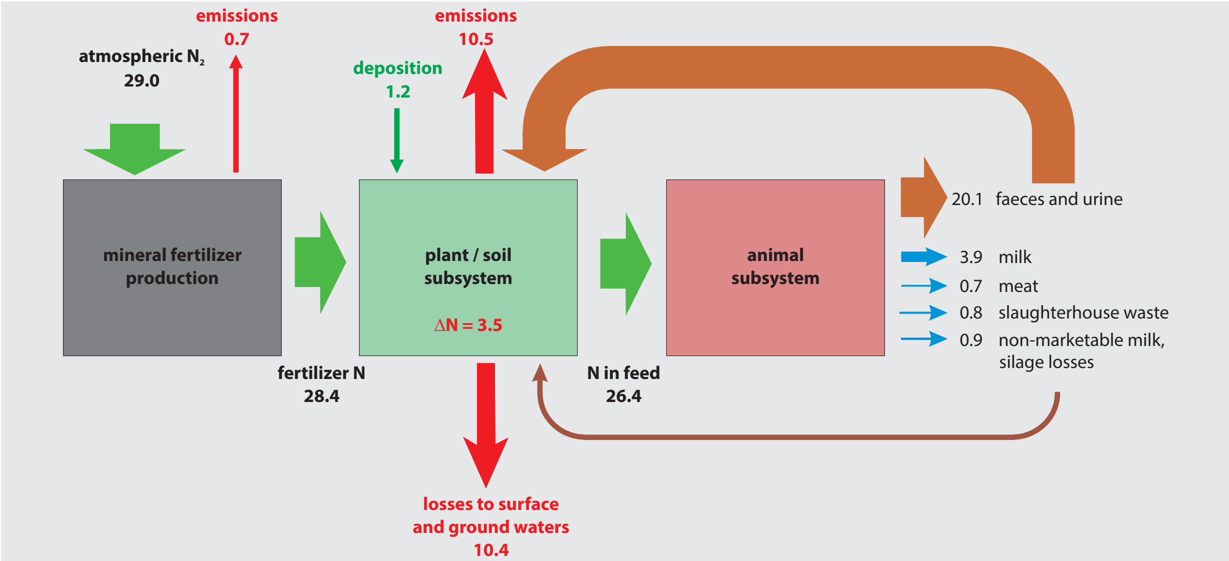

Figure 17
N balance for the reference farm. Fluxes in Mg herd^{-1} lactation^{-1}. ΔN in the plant soil subsystem indicates the amount of N that may be stored as additional soil N.

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 %

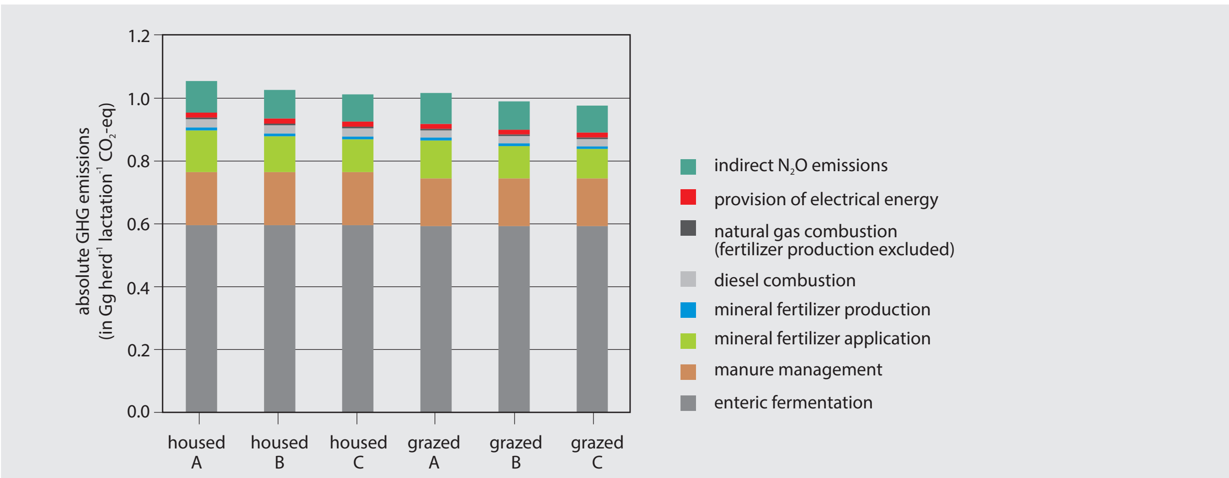

Figure 18
Absolute GHG emissions for reduced mineral fertilizer input (other variables reference values). housed: all animals are housed except dairy heifers (see above): grazed: all dairy cows are grazed part time (8 h d^{-1} during grazing period, 150 d a^{-1}); dairy heifers as above. All other animals 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 $EF_{\text{NH3, SU}}$ = 0.243 kg kg^{-1} NH_3-N, factor $EF_{\text{NH3, UAN}}$ = 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).

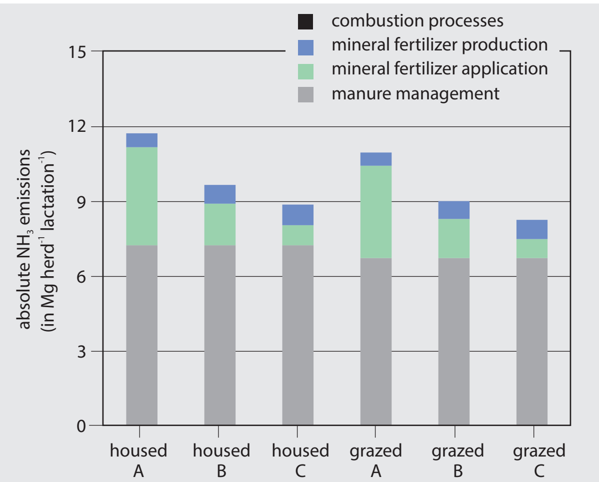

Figure 19
Absolute NH_3 emissions for reduced mineral fertilizer input (other variables reference values) . housed: all animals are housed except dairy heifers (see above): grazed: all dairy cows are grazed part time (8 h d^{-1} during grazing period, 150 d a^{-1}); dairy heifers as above. All other 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.

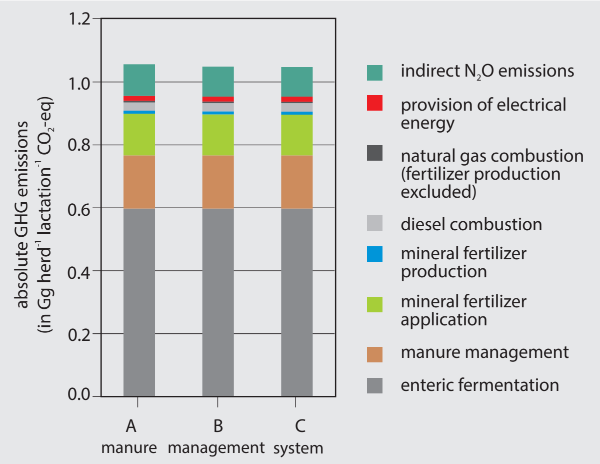

Figure 20
Changes in GHG emissions resulting from modified manure application and incorporation (for variants A, B and C see Table 7)

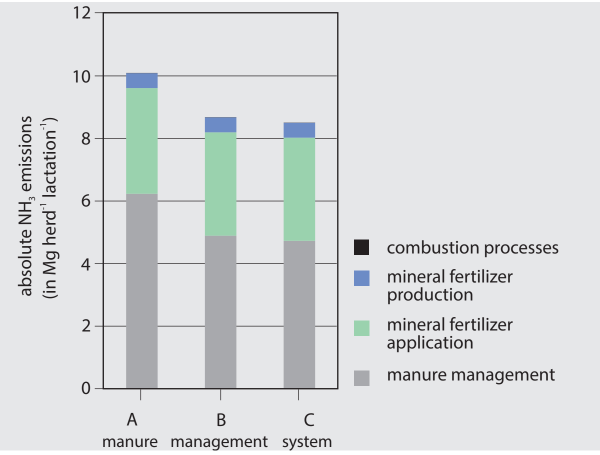

Figure 21
Changes in NH_3 emissions resulting from modified manure application and incorporation (for variants A, B and C see Table 7)

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

[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.

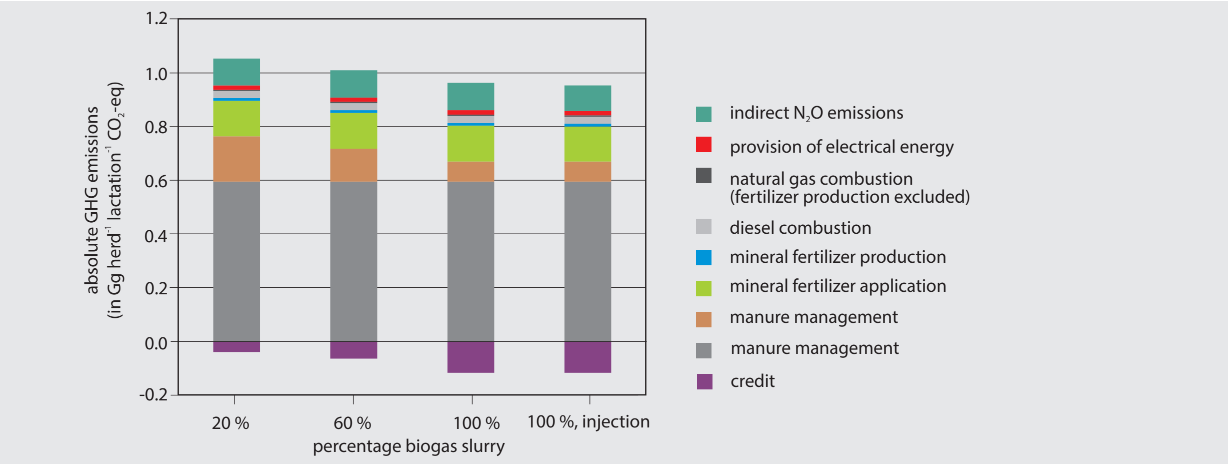

Figure 22
GHG emissions per herd as a function of the share of slurry digested in biogas production (percent of slurry digested; last column using injection on arable land and trailing hose on grassland exclusively, all other variables as reference)

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.

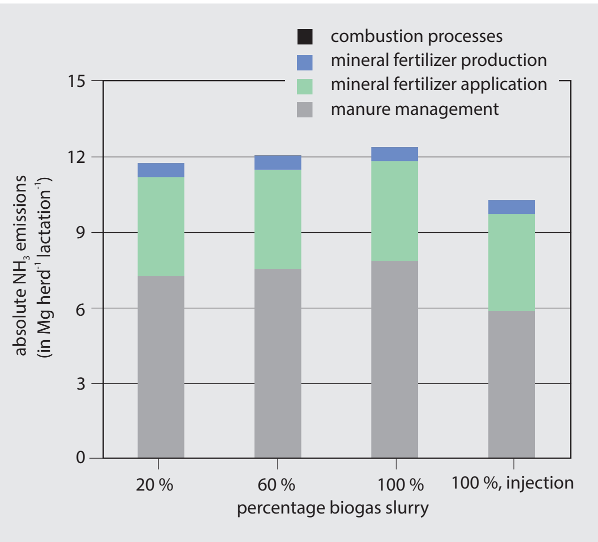

Figure 23
NH_3 emissions per herd as a function of the share of slurry digested in biogas production (percent of slurry digested; last column using injection on arable land and trailing hose on grassland exclusively, all other variables as in reference herd)

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.

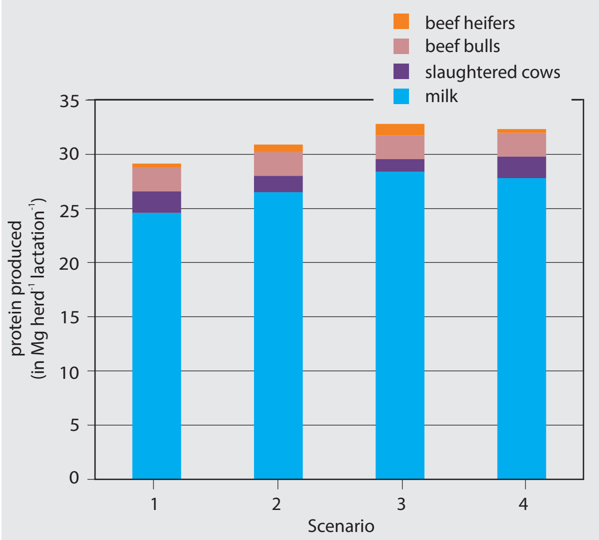

Figure 24
Contributions of animal categories to protein production in Scenarios 1 to 4

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

[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

[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.

Acknowledgement

Leibniz Institute for Farm Animal Biology supported UD which is gratefully acknowledged.

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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

DOI:10.3220/LBF1480077043000

Gasförmige Emissionen bei der Eiweißerzeugung mit Deutschen Holsteins – eine Stoffstromanalyse der gesamten Produktionskette 3. Bewertung der Milchkuhhaltung in einer grünlandbasierten Milcherzeugung bei begrenztem Kraftfuttereinsatz

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Zusammenfassung

Angesichts notwendiger Emissionsminderungen in der deutschen Landwirtschaft berechnet und bewertet die vorliegende Arbeit gasförmige Emissionen (Ammoniak, Treibhausgase) bei der Milcherzeugung auf Grünlandstandorten bei limitierter Kraftfutterzufütterung. Die Erfassung schließt die Vorkette (Futtererzeugung, Bereitstellung von Düngern, Wasser und elektrischer Energie) ein.

Unter vergleichbaren Bedingungen (Kraftfutterzufütterung, gleiche Grundfutterqualitäten, Leistungsniveau etc.) erweist sich eine saisonale Weidehaltung im Vergleich zu einer ganzjährigen Stallhaltung als vorteilhaft; vor allem bezüglich der Ammoniak-Emissionen. Dabei sollte die Dauer der Weideperiode so lange wie betrieblich möglich ausgedehnt werden.

Eine regelmäßige Kraftfuttersupplementierung ist vor allem dann zu empfehlen, wenn nur mäßige Erträge und Gras- bzw. Grassilagequalitäten auf dem Grünland erzeugt werden können. Die richtige Wahl des Kraftfutters – vor allem bezüglich seines Proteingehaltes – trägt bereits zur Emissionsminderung bei.

Schlüsselwörter: *Emission, Ammoniak, Treibhausgase, Milchkuh, Grünland, Weide*

Abstract

Gaseous emissions arising from protein production with German Holsteins – an analysis of the energy and mass flows of the entire production chain 3. Assessment of dairy cow husbandry in grassland-based milk production with limited supply of concentrates

Emission reduction in German agriculture has become a necessity. This paper deals with the calculation and assessment of gaseous emissions (ammonia, greenhouse gases) from grassland-based milk production with limited supply of concentrates. This includes the emissions from the entire production chain (feed and fertilizer production, provision of water and electrical energy).

Under comparable conditions (supplementing with concentrates, roughage quality, performance etc.) grazing proves to be favourable as compared to exclusive housing, in particular for ammonia emissions. The grazing period should be extended to the maximum duration operationally possible.

Regular supplementing with concentrates is recommended, in particular, if the yields of grassland or grass and silage qualities are moderate. The choice of a concentrate with adequate protein content helps reducing emissions.

Keywords: *emission, ammonia, greenhouse gases, dairy cows, grassland, grazing*

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1 Einleitung

Die Produktion von Milch und Rindfleisch ist zwangsläufig mit Emissionen von Treibhausgasen (vor allem Methan, CH_4, und Lachgas, N_2O) und luftverschmutzenden Gasen (vor allem Ammoniak, NH_3) verbunden. Hierbei kommt den CH_4- und NH_3-Emissionen aus der Milchkuhhaltung besondere Bedeutung zu. Es ist daher sinnvoll, dass emissionsmindernde Maßnahmen in der Landwirtschaft schwerpunktmäßig bei der Milchproduktion ansetzen und dabei die gesamte Produktionskette einschließlich des Koppelprodukts Rindfleisch in die Überlegungen einbeziehen.

Innerhalb der EU wurde jüngst eine Verschärfung von Emissionsobergrenzen, speziell auch für NH_3-Emissionen und für zu einem erheblichen Teil aus NH_3-Emissionen herrührenden Sekundärfeinstaub-Belastungen, empfohlen (EU, 2016). Deutschland ist allerdings jetzt schon nicht in der Lage, die nationale Emissionsobergrenze für NH_3 einzuhalten; die Emissionen sind in den vergangenen Jahren deutlich gestiegen (Haenel et al., 2016). Im Bereich der Treibhausgase erfüllt Deutschland zurzeit seine Verpflichtungen. Erhebliche weitergehende Minderungen sind allerdings geplant (UBA, 2015). Dabei wird den CH_4-Emissionen, die aus der enterischen Fermentation der Wiederkäuer resultieren, (vorerst) noch eine Sonderstellung zugebilligt werden.

Im Rahmen der bisherigen Aktivitäten wurden bereits komplette Mutterkuhherden (mit Nachzucht) zur Rindfleischerzeugung (Dämmgen et al., 2015) und die konventionelle Proteinerzeugung (Milch/Fleisch) mit Einnutzungsrindern (Deutsche Holsteins) bei hohen Laktationsleistungen und intensivem Kraftfuttereinsatz modelliert (Dämmgen et al., 2016 a, b). Es zeigte sich, dass Emissionsminderungen vor allem dadurch zustande kommen, dass an zahlreichen ‚Schaltstellen' (etwa Verringerung der Tierverluste, längere Lebensdauer der Milchkühe, Verringerung des Harnstoffeinsatzes in der Futterproduktion, usw.) jeweils geringe Erfolge erzielt werden können, deren Summe dann aber bedeutend und deren Zusatzkosten gering sind.

Aus betriebswirtschaftlicher Sicht ist ebenfalls zu bedenken, dass sich bei Verbrauchern ein Kaufverhalten einzustellen beginnt, das dazu führt, dass Molkereien zunehmend die Weidehaltung von Kühen als ein zusätzliches Verkaufsargument einsetzen. Gesichtspunkte sind dabei die Naturbelassenheit der Lebensmittel (z. B. FrieslandCampina: ‚Weidemilch') (Menzel et al., 2015; Milieudefensie, 2015). Aspekte der Tiergesundheit und des Wohlbefindens finden sich z. B. bei Olmos et al. (2009), Burow et al. (2011), Wagner et al. (2015). Eine gegenüber der Stallhaltung verringerte Verletzungsgefahr auf der Weide führen Armbrecht et al. (2015) an. Demgegenüber ist Weidegang bei hohen Proteingehalten des Weidefutters mit verringerter N-Effizienz verbunden. Weidehaltung bedeutet ebenfalls höhere Abhängigkeit vom Wettergeschehen, erhöhten Arbeitsaufwand etc. (zu einer ausführlichen Diskussion siehe Schären et al., 2016).

Bisher wurde bei unseren Arbeiten die Erzeugung von Milcheiweiß bei konsequenter Weidehaltung und sehr begrenztem Kraftfuttereinsatz in Grünlandregionen nicht berücksichtigt. Auch in der internationalen Literatur sind kaum entsprechende Arbeiten zu dieser Thematik zu finden (O'Mara, 2004).

Mit der vorliegenden Arbeit sollen die gasförmigen Emissionen bei begrenztem Kraftfuttereinsatz und unterschiedlicher Dauer der saisonalen Weidehaltung am Beispiel von Holstein-Kühen untersucht werden. Eine konsequente Nutzung von Grünland ist vor allem in solchen Regionen zu suchen, in denen ackerbaufähige Böden und somit alternative Nutzungsmöglichkeiten mittels Wiederkäuern kaum vorhanden sind. Damit sind notwendige Kraftfuttergaben für Milchkühe vorrangig durch Zukauf bereit zu stellen. Aus volks- und betriebswirtschaftlicher Sicht interessiert dabei ein nur geringer Kraftfuttereinsatz in besonderer Weise.

Angesichts der Tatsache, dass die Proteinerzeugung einer Herde zu über 80 % aus der Milch resultiert (Dämmgen et al., 2016 b), soll allerdings nicht die gesamte Produktionskette betrachtet werden, sondern lediglich die aus der Haltung der Milchkühe und der zur Bereitstellung von Futter, Wasser und Energie resultierenden Emissionen.

2 Material und Methoden

2.1 Modelle

Genutzt wird das Milchkuhmodell von Dämmgen et al. (2009) in modifizierter Form (siehe Haenel et al., 2016), das Ausscheidungen als Funktion der Leistung (Milchmenge und -zusammensetzung, Lebendmasse, tägliche Zunahme) und der Futterqualität berechnet. Es wird hier invertiert: Eingangsgrößen sind nunmehr Futtermengen und Futtereigenschaften; die Milchleistung (bei gegebenen Fett- und Eiweißkonzentrationen) und gegebenem Einsatz an Kraftfutter wird für unterschiedliche Weidedauern und Grundfutterqualitäten berechnet.

Im zweiten Schritt werden die Emissionen aus der Vorkette quantifiziert. Hier werden die in Dämmgen et al. (2016a) beschriebenen Verfahren zur Ableitung des Bedarfs an Düngemitteln, Wasser und Energieträgern angewendet und die bei ihrer Bereitstellung und Anwendung entstehenden Emissionen berechnet.

2.2 Herde und Systemgrenzen

Betrachtet werden Kühe einer konstant großen Milchkuhherde (Deutsche Holsteins, mittlere Lebendmasse 650 kg Kuh^{-1}, mittlere Zunahme 20 kg Kuh^{-1} a^{-1}; Milchfett- und Milcheiweißgehalte von 4,0 bzw. 3,5 %) sowie zugehörige vorgelagerte Prozesse (Futterbereitstellung) und nachgelagerte Prozesse (Wirtschaftsdüngermanagement). Aufzucht dagegen wird nicht berücksichtigt.

Eingeschlossen sind die direkten und indirekten Emissionen aus

- dem tierischen Stoffwechsel (CH_4) und aus Futterkalk (CO_2),
- dem Wirtschaftsdüngermanagement (Stall, Lager, Ausbringung; NH_3, N_2O, NO, N_2, CH_4),
- dem Verrotten von auf dem Feld verbliebenen Futterpflanzenresten (N_2O),

- der Lagerung der Silageabfälle aus Entnahmeverlusten (N_2O, CH_4),
- der Anwendung von Mineraldüngern und Düngekalk (NH_3, N_2O, NO, CO_2),
- der Bereitstellung von Mineraldünger und Kalk (THG [1]) sowie
- der Bereitstellung von Wasser und elektrischer Energie (THG).

Unabhängig davon, ob der Betrieb selbst Ackerflächen bewirtschaftet, werden die Emissionen für die Bereitstellung von Kraftfutter den Kühen zugerechnet. Es wird davon ausgegangen, dass der Ackerbetriebszweig dann Gülle vom Grünlandbetriebszweig erhält.

Die Remontierung der Herde wird unabhängig von der Milchkuhhaltung als gegeben vorausgesetzt; sie ist somit eine konstante Größe und für die hier bearbeitete Fragestellung letztlich bedeutungslos. [2]

Nicht eingeschlossen sind Emissionen aus

- dem Stoffwechsel der Tiere (außer CH_4)
- der Bereitstellung von Mengen- und Spurenelementen sowie Vitaminzusätzen,
- der Bereitstellung von Tiermedizin, Futterzusätzen sowie Silierhilfen
- der Entsorgung von nicht marktfähiger Milch mit der Gülle oder
- dem Transport von Tieren und Futter.

Die Emissionen werden je Tier sowie produktbezogen auf die Menge verkaufsfähiger Milch angegeben.

2.3 Rationszusammensetzung und Futtermitteleigenschaften

Die nachfolgend berücksichtigten Rationen sind – entsprechend der Zielsetzung der Arbeit – klar gras- bzw. grassilagebetont. Die weitere Kraftfuttersupplementierung variiert sowohl in der Menge als auch Qualität. Die Zusammensetzung der Milchleistungsfutter (MLF; Konzentratfutter) basiert auf Futtermitteln, die auf heimischen Märkten angeboten werden. (Zu den Futtereigenschaften siehe Tabellen 1 bis 3.)

Eine gras- bzw. grassilage-basierte Fütterung enthält im Gegensatz zu einem Grundfutter mit ausschließlichem Einsatz von Maissilage bereits relativ viel Rohprotein. Genutzt

Tabelle 1
Eigenschaften von Kraftfutter und Kraftfuttermitteln (Daten nach DLG, 1997 und Beyer et al., 2004)

		Gehalte bezogen auf T						scheinbare Verdaulichkeit
	T* kg kg^{-1}	NEL MJ kg^{-1}	XP kg kg^{-1}	XL kg kg^{-1}	XX kg kg^{-1}	XF kg kg^{-1}	XA kg kg^{-1}	OS kg kg^{-1}
Gerste	0,88	8,08	0,124	0,027	0,765	0,057	0,027	0,85
Weizen	0,87	9,00	0,145	0,020	0,785	0,030	0,020	0,88
Roggen	0,88	8,49	0,112	0,018	0,822	0,027	0,021	0,90
Rapsextraktionsschrot*	0,91	7,12	0,400	0,020	0,345	0,150	0,085	0,77
Mineralgemisch	0,97						1,000	
Kalk	0,97						1,000	
MLF 16/3	0,88	6,86	0,137	0,018	0,605	0,172	0,068	0,76
MLF 14/3	0,88	6,89	0,121	0,018	0,629	0,167	0,065	0,77

* Abkürzungen nach GfE: T Trockenmasse; NEL Nettoenergie-Laktation; XP Rohprotein; XL Rohfett; XX N-freie Extraktstoffe; XF Rohfaser; XA Rohasche; OS organische Substanz

Tabelle 2
Eigenschaften von Futterzusatzmitteln (Daten nach Beyer et al., 2004)

		Gehalte bezogen auf T						scheinbare Verdaulichkeit
	T* kg kg^{-1}	NEL MJ kg^{-1}	XP kg kg^{-1}	XL kg kg^{-1}	XX kg kg^{-1}	XF kg kg^{-1}	XA kg kg^{-1}	OS kg kg^{-1}
Stroh	0,850	3,80	0,040	0,017	0,425	0,450	0,070	0,47
Trockenschnitzel	0,900	7,40	0,095	0,005	0,645	0,200	0,055	0,80

[1] Wenn die beim jeweiligen Prozess freigesetzten THG nicht einzeln aufgeführt werden, erfolgt die Angabe pauschal als THG.

[2] Eine detaillierte Bewertung der Kälber- und Färsenaufzucht sowie des Koppelprodukts „Fleisch" findet sich in vorangegangenen Arbeiten, insbesondere in Dämmgen et al., 2016 a, b).

Tabelle 3
Grundfuttereigenschaften (nach DLG, 1997)

	Gehalte bezogen auf T								scheinbare Verdaulichkeit
	Ertrag (T) Mg ha^{-1}	T kg kg^{-1}	NEL MJ kg^{-1}	XP kg kg^{-1}	XL kg kg^{-1}	XX kg kg^{-1}	XF kg kg^{-1}	XA kg kg^{-1}	OS kg kg^{-1}
Weidegras g *	10,0	0,170	6,90	0,180	0,037	0,496	0,195	0,092	0,80
Weidegras m	7,5	0,210	5,88	0,130	0,030	0,470	0,288	0,082	0,71
Grassilage g	10,0	0,350	6,51	0,171	0,046	0,456	0,212	0,115	0,81
Grassilage m	7,5	0,350	5,84	0,149	0,040	0,426	0,273	0,112	0,72

* g gute Grundfutterqualität; m mäßige Grundfutterqualität

werden daher im Gegensatz zur dort eher üblichen Praxis die beiden folgenden MLF-Qualitäten:

- MLF 16/3 (mit 16 % Rohprotein in der Energiestufe 3);
- MLF 14/3 (mit 14 % Rohprotein in der Energiestufe 3).

Da in der Praxis sehr unterschiedliche natürliche Weidebedingungen (Boden, Klima, Ertragsniveau, Weidemanagement etc.) anzutreffen sind, werden zusätzlich zwei unterschiedliche Gras-/Grassilage-Qualitäten nachfolgend berücksichtigt. Diese Grundfutterqualitäten unterscheiden sich sowohl im Energie- und Proteingehalt als auch im Ertragsniveau, wie beispielhaft der Arbeit von Albers und Backes (2012) zu entnehmen ist.

Die Berechnung der Emissionen berücksichtigt ausschließlich Futtermengen und die in der Weender Analyse bereitgestellten Eigenschaften.

2.4 Haltung und Wirtschaftsdünger-Management, Mineraldüngereinsatz

2.4.1 Haltung und Wirtschaftsdüngermanagement

Die Emissionen aus dem Wirtschaftsdüngermanagement gehen von folgenden Randbedingungen aus:

- Boxenlaufstall mit Flüssigmist,
- Lager mit natürlicher Schwimmdecke,
- Ausbringung mit Schleppschlauch, je zur Hälfte auf dem Acker und auf Grünland,
- Einarbeitung auf dem unbestellten Acker innerhalb von vier Stunden.

2.4.2 Mineraldüngereinsatz

Der Düngerbedarf für die einzelnen Futtermittel wird aus den Anbauflächen (unter Berücksichtigung der Allokation bei Koppelprodukten über deren Bruttoenergie) und bei Ackerfrüchten anhand der geltenden Empfehlungen der Düngeverordnung (DüV; hier LWK-Nds, 2013) ermittelt.

Für Weidegras und Silage wird der N-Bedarf aus dem Entzug berechnet. Berücksichtigt werden N-Verluste durch Emissionen in Höhe von 5 % sowie eine Versickerungspauschale von 30 % der eingesetzten N-Menge nach IPCC (2006).

Tabelle 4
Übersicht über in den Rechnungen variierte Eingangsgrößen

Szenario	Kraftfutter MLF-Typ	Kraftfutter Menge (in Mg Kuh^{-1} a^{-1} FM)	Grundfutterqualität	Weidetage (in d a^{-1})
14/1/g/000	14/3	1,0	gut	0
14/2/g/000	14/3	2,0	gut	0
14/1/g/075	14/3	1,0	gut	75
14/2/g/075	14/3	2,0	gut	75
14/1/g/150	14/3	1,0	gut	150
14/2/g/150	14/3	2,0	gut	150
16/1/g/000	16/3	1,0	gut	0
16/2/g/000	16/3	2,0	gut	0
16/1/g/075	16/3	1,0	gut	75
16/2/g/075	16/3	2,0	gut	75
16/1/g/150	16/3	1,0	gut	150
16/2/g/150	16/3	2,0	gut	150
14/1/m/000	14/3	1,0	mäßig	0
14/2/m/000	14/3	2,0	mäßig	0
14/1/m/075	14/3	1,0	mäßig	75
14/2/m/075	14/3	2,0	mäßig	75
14/1/m/150	14/3	1,0	mäßig	150
14/2/m/150	14/3	2,0	mäßig	150
16/1/m/000	16/3	1,0	mäßig	0
16/2/m/000	16/3	2,0	mäßig	0
16/1/m/075	16/3	1,0	mäßig	75
16/2/m/075	16/3	2,0	mäßig	75
16/1/m/150	16/3	1,0	mäßig	150
16/2/m/150	16/3	2,0	mäßig	150

Der Bedarf an Düngekalk, Phosphor und Kalium wird KTBL (2014) entnommen.

Der mit Mineraldünger aufzubringende N errechnet sich aus dem Bedarf aller Futterpflanzen und den mit dem Wirtschaftsdünger aufgebrachten N-Mengen. Dabei wird das Mineraldüngeräquivalent (MDÄ) zum einen nach LWK-Nds

(2013) mit 0,6 kg kg^{-1} angesetzt, zum zweiten nach dem (Januar 2016) aktuellen Entwurf der Düngeverordnung (BMEL, 2015; Acker: 0,7, Weide 0,4 kg kg^{-1}), zum dritten nach dem Stand des Wissens mit 0,8 kg kg^{-1} (Schröder, 2005; vgl. Anwendung im benachbarten Ausland, Döhler, 2016). Als N-Mineraldünger wird ausschließlich Kalkammonsalpeter (KAS) verwendet (wie in den Produktionskenndaten und Verfahrensübersichten in KTBL, 2014).

2.5 Szenarien

In Tabelle 4 sind die berücksichtigten Fütterungsvarianten zusammengestellt und die für die Szenarien benutzten Kürzel erläutert. Neben unterschiedlichen Grundfutterqualitäten (gut und mäßig, vgl. Tabelle 3) werden außerdem Kraftfuttertyp und -menge sowie die Dauer des Weidegangs im Jahr bei einer täglichen Weidedauer von 12 h variiert. Zusätzlich werden im Stall ganzjährig 1 kg Kuh^{-1} d^{-1} Stroh (Frischmasse, FM) sowie Trockenschnitzel verabreicht (2 kg Kuh^{-1} d^{-1} FM während der ersten 150 Tage der Laktation).

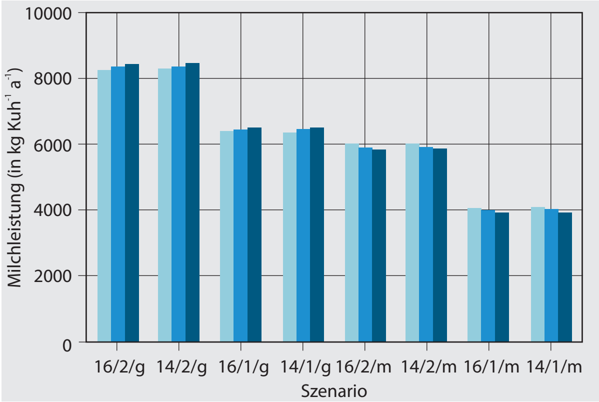

Abbildung 1
Milchleistung je Kuh und Jahr in Abhängigkeit von Kraftfutterart und -menge, der Grundfutterqualität sowie der Anzahl der Weidetage. Hellblau: keine Weide; mittelblau: Halbtagsweide 75 d a^{-1}; dunkelblau: Halbtagsweide 150 d a^{-1}. (Zu Details siehe Tabelle A1 im Anhang, zur Kennzeichnung der Szenarien siehe Tabelle 4.)

2.6 Berechnung der Emissionen

Die Berechnung bedient sich der Methoden des Nationalen Emissionsinventars. Zu Einzelheiten siehe Haenel et al. (2016) (landwirtschaftliches Inventar) und Dämmgen et al. (2016 a) (Emissionen aus der Vorkette: Futter-, Dünger- und Wasserbereitstellung, Verbrennungsmaschinen und Industrieanlagen). [3]

3 Ergebnisse

3.1 Milchleistung als Funktion der Fütterung

Der Energiebedarf von Milchkühen setzt sich aus den jeweils erforderlichen Anteilen für die Erhaltung, für die Milchbildung (dominierend), für das Wachstum von Fetus und weiterem Gewebe im Verlauf der Laktation bzw. der Trächtigkeit und für Bewegung zusammen. In unserer Untersuchung stellt sich die Milchleistung in Abhängigkeit von Futterqualität und Bewegung (Dauer des Weidegangs) unter den in Abschnitt 2.5 genannten Randbedingungen ein (Abbildung 1).

Deutlich erkennbar in Abbildung 1 ist der Einfluss der Kraftfuttermenge auf die Milchleistung. Auch die Grundfutterqualität ist von entscheidender Bedeutung. Die Dauer der Weidehaltung bei differenzierten Grundfutterqualitäten beeinflusst die Höhe der Milchleistung insgesamt gering. Beobachtet werden bei gutem Grundfutter zunehmende Leistungen im Vergleich zur ganzjährigen Stallhaltung, da der Energiegehalt der Silage gegenüber dem Weidefutter durch die Silierverluste abnimmt. Bei mäßigem Grundfutter ist das Gegenteil zu beobachten. Mit zunehmender Dauer des Weidegangs steigt der Anteil der Bewegungsenergie auf Kosten der Laktationsenergie spürbar (Tabelle 5). Bei hohem NEL-Gehalt des Grundfutters wird dies beim Weidegang überkompensiert, bei mäßiger Qualität wird der Effekt voll wirksam. Der Energiebedarf pro Tier für die Entwicklung der Konzeptionsprodukte [4] *pro Tier* ist konstant. Die hier durchgeführten Rechnungen *pro Jahr* berücksichtigen, dass die Dauer der Zwischenkalbezeit eine Funktion der Milchleistung ist. Der *pro Jahr* anfallende Anteil des NEL-Bedarfs für die Entwicklung der Konzeptionsprodukte ist daher variabel.

Da der NEL-Gehalt der beiden Kraftfuttertypen praktisch gleich ist, unterscheiden sich die Milchleistungen kaum beim Wechsel von MLF 14/3 zu MLF 16/3.

Tabelle 5
Berechneter Futterenergiebedarf für gute und mäßige Grundfutterqualitäten bei unterschiedlicher Dauer des Weidegangs (in GJ Kuh^{-1} a^{-1} NEL)

Energiebedarf für	gute Grundfutterqualität Weidetage (in d a^{-1})			mäßige Grundfutterqualität Weidetage (d a^{-1})		
	0	75	150	0	75	150
Erhaltung	17,10	17,10	17,10	17,10	17,10	17,10
zusätzliche Bewegung	0,00	0,30	0,60	0,00	0,30	0,60
Laktation	20,98	21,33	21,54	13,53	13,27	13,01
Konzeptionsprodukte	0,847	0,845	0,844	0,886	0,887	0,889
Wachstum	0,51	0,51	0,51	0,51	0,51	0,51
Summe	39,44	40,09	40,60	32,03	32,07	32,11

[3] Futtermengen und Düngerbedarf, Treibstoffeinsatz, Emissionen aus der Pflanzenproduktion: Kap. 2.5; Bereitstellung von Mineraldüngern und Kalk mit ihren Emissionen: Kap. 2.6; Mischfutterherstellung: Kap. 2.8; Bereitstellung von Wasser und Energieträgern: Kap. 2.9

[4] fasst den Bedarf für das Wachstum von Fetus und weiterem Gewebe im Verlauf der Trächtigkeit zusammen

3.2 Ammoniak-Emissionen als Funktion von Fütterung und Düngung

In Tabelle 6 sind die NH_3-Emissionen zweier Szenarien mit und ohne Weidegang gegenübergestellt. Hierbei ist zu bedenken, dass insbesondere die Emissionen bei der Ausbringung stark von der Technik und der Zeit vor der Einarbeitung abhängen, die hier nicht variiert werden. Für unsere Betrachtungen ist wichtig, dass die Zwischensumme der Emissionen aus dem Stall, dem Lager und der Weide deutlich zugunsten der Weide ausfällt:

Tabelle 6
Beispielhafte NH_3-Emissionen in kg Kuh^{-1} a^{-1} NH_3, aufgeschlüsselt nach ihrer Entstehung, Düngung nach geltender DüV (LWK-Nds, 2013)

	Szenario	
Ort bzw. Prozess	14/2/g/000	14/2/g/150
Stall	16,0	13,1
Weide	0,0	1,7
Lager	3,0	2,5
Ausbringung	21,1	17,3
Silageabfälle aus Entnahmeverlusten	1,0	0,8
Mineraldünger-Anwendung	5,1	4,9
Mineraldünger-Herstellung	11,5	11,2
Summe	57,6	51,5

Die Ausscheidungen auf der Weide sind mit deutlich geringeren NH_3-Emissionen als im Stall verbunden, weil das mit dem Harn ausgeschiedene N alsbald vom Boden aufgenommen und dort gebunden wird. Bei Weidegang gelangen geringere N-Mengen aus dem Stall ins Lager und zur Ausbringung.

Da weniger Silage gefüttert wird, verringern sich die Silier- und Entnahmeverluste. Daher muss bei Weidehaltung insgesamt weniger Gras erzeugt werden, was zu einem verringerten Mineraldüngereinsatz führt und damit zu geringeren Emissionen bei deren Anwendung und Herstellung.

Die NH_3-Emissionen je Kuh und Jahr sind in Abbildung 2, die auf die Menge verkaufter Milch bezogenen Emissionen in Abbildung 3 dargestellt. Dabei wurde der Mineraldüngerbedarf nach der geltenden DüV berechnet. Abbildung 4 veranschaulicht den Einfluss der unterschiedlichen angenommenen Mineraldüngeräquivalente der Wirtschaftsdünger bei der Berechnung des anfallenden Mineraldüngerbedarfs bei gleich bleibenden Erträgen.

Die Ergebnisse dieser Rechnungen lassen sich wie folgt zusammenfassen:

- Weidehaltung reduziert gegenüber einer ganzjährigen Stallhaltung die NH_3-Emissionen sowohl absolut als auch produktbezogen (in g kg^{-1} Milch).
- Falls Weide betrieblich möglich ist, dann ist eine lange Weidedauer anzustreben.
- Eine Kraftfuttersupplementierung ist auch unter Weidebedingungen generell vorteilhaft, da das Leistungsniveau angehoben wird. Die Verdoppelung der Kraftfuttergabe hat kaum Einfluss auf die absoluten Emissionen, reduziert aber die produktbezogenen Emissionen wegen der erhöhten Milchleistung erheblich.
- Das Verfüttern von MLF16/3 führt aufgrund der erhöhten N-Aufnahme und -Ausscheidung zu höheren NH_3-Emissionen als das von MLF14/3.
- Die Annahme einer verbesserten Wirtschaftsdüngerwirksamkeit (erhöhte MDÄ-Werte) führt zu einer deutlichen Verringerung des Mineraldüngereinsatzes und verbessert damit die N-Produktivität der Milchproduktion. Die Auswirkungen auf die NH_3-Emissionen sind allerdings gering (Abbildung 4); die überwiegende Menge der Emissionen entsteht beim Wirtschaftsdünger-Management. Eine merkliche, wenn auch geringe Minderung erbringt das verbesserte Rechenverfahren, das 90 % der Wirtschaftsdünger-N-Einträge als wirksam betrachtet.

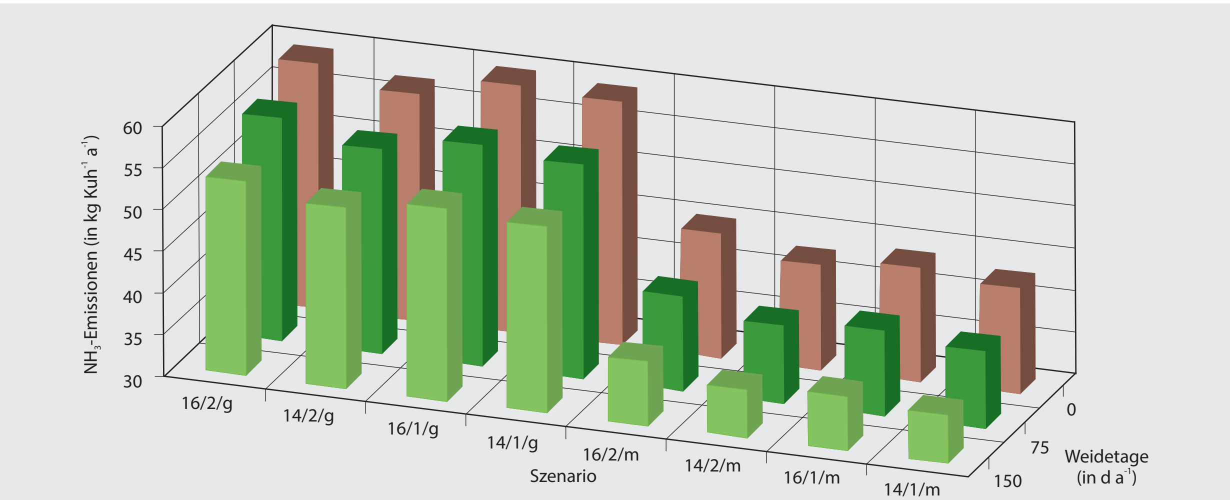

Abbildung 2
NH_3-Emissionen je Kuh und Jahr in Abhängigkeit von Kraftfutterart und -menge, der Grundfutterqualität sowie der Anzahl der Weidetage, Düngung nach geltender DüV (LWK-Nds, 2013). Zu Details siehe Tabellen A2 und A3 im Anhang.

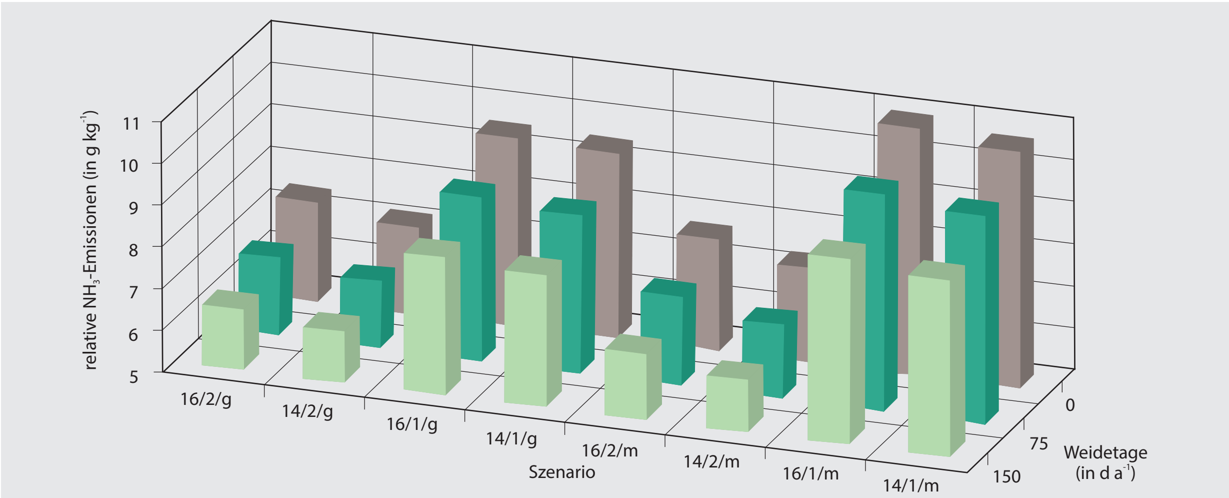

Abbildung 3
NH_3-Emissionen je kg verkaufter Milch in Abhängigkeit von Kraftfutterart und -menge, Grundfutterqualität sowie der Anzahl der Weidetage, Düngung nach geltender DüV (LWK-Nds, 2013). Zu Details siehe Tabellen A4 und A5 im Anhang.

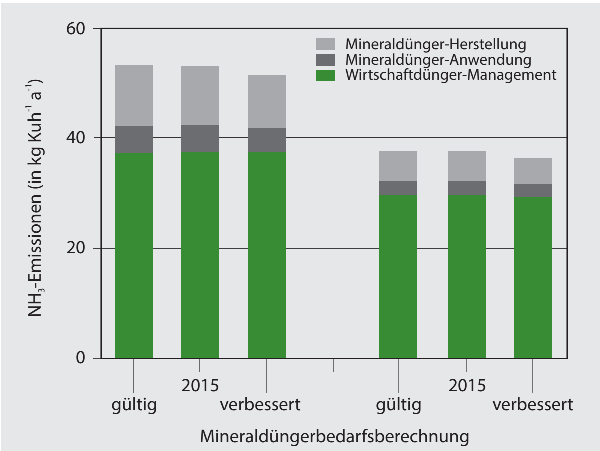

Abbildung 4
Einfluss der gewählten Mineraldüngeräquivalente (derzeit gültige DüV, Entwurf 2015 der DüV, verbesserte MDÄ) auf die NH_3-Emissionen (Szenarien 16/2/g150, links, und 16/2/m/150, rechts)

3.3 Treibhausgas-Emissionen als Funktion von Fütterung und Düngung

Betrachtet werden die Emissionen von CH_4 aus der Verdauung und dem Wirtschaftsdünger-Management, von N_2O aus dem Wirtschaftsdüngermanagement, der Mineraldüngeranwendung und -produktion, aus verrottenden Pflanzenresten und als indirekte Emissionen aus der Wirkung von NH_3 und Ammonium (NH_4^+) sowie Stickstoffdioxid (NO_2) und Nitrat (NO_3^-) in der atmosphärischen Deposition sowie N_2O aus N-Austrägen mit dem Oberflächenabfluss und ins Grundwasser. CO_2 entsteht bei den Verbrennungsprozessen (Diesel, Erdgas) und der Anwendung von Kalk (Düngekalk, Kalkammonsalpeter, Futterkalk). Nicht weiter aufgeschlüsselte THG-Emissionen (siehe Fußnote 2) werden für die Bereitstellung der Energieträger (einschließlich elektrischer Energie) berücksichtigt.

Die Klimawirksamkeit der unterschiedlichen Gase wird über ihre Treibhausgaspotenziale berücksichtigt und in CO_2-Äquivalenten angegeben (IPCC, 2007. CO_2: 1 kg kg^{-1} CO_2-eq; CH_4: 25 kg kg^{-1} CO_2-eq; N_2O: 298 kg kg^{-1} CO_2-eq).

Tabelle 7 gibt eine Übersicht über Entstehungsorte. Es wird deutlich, dass das gesamte Emissionsgeschehen von den Emissionen aus der Verdauung dominiert wird. Die Abbildungen 5 und 6 fassen die Ergebnisse der Modellrechnungen zusammen. Die detaillierten Zahlen hierzu sind den Tabellen A6 bis A9 im Anhang zu entnehmen. In Abbildung 7 ist der Einfluss der für die Rechnung gewählten Mineraldüngeräquivalente dargestellt.

Tabelle 7
Beispielhafte THG-Emissionen in Mg Kuh^{-1} a^{-1} CO_2-eq, aufgeschlüsselt nach ihrer Entstehung

	Szenario	
Ort bzw. Prozess	14/2/g/000	14/2/g/150
Verdauung	3,30	3,38
Wirtschaftsdüngermanagement (einschl. Weidegang)	0,79	0,65
Mineraldünger-und Kalk-Anwendung	1,28	1,25
Mineraldünger-Herstellung	0,27	0,26
Verbrennen von Diesel und Heizöl	0,16	0,14
Verbrennen von Erdgas	0,13	0,13
Bereitstellung elektrischer Energie	0,09	0,09
indirekte N_2O-Emissionen	0,54	0,51
Summe	6,55	6,42

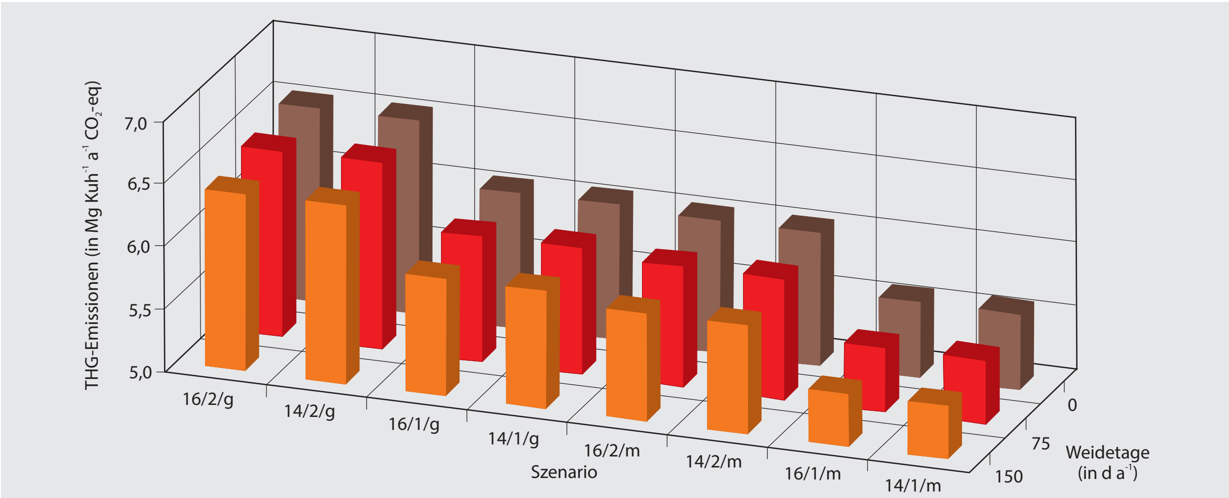

Abbildung 5
THG-Emissionen je Kuh und Jahr in Abhängigkeit von Kraftfutterart und -menge, Grundfutterqualität sowie der Anzahl der Weidetage, Düngung nach geltender DüV (LWK-Nds, 2013). Zu Details siehe Tabellen A6 und A7 im Anhang.

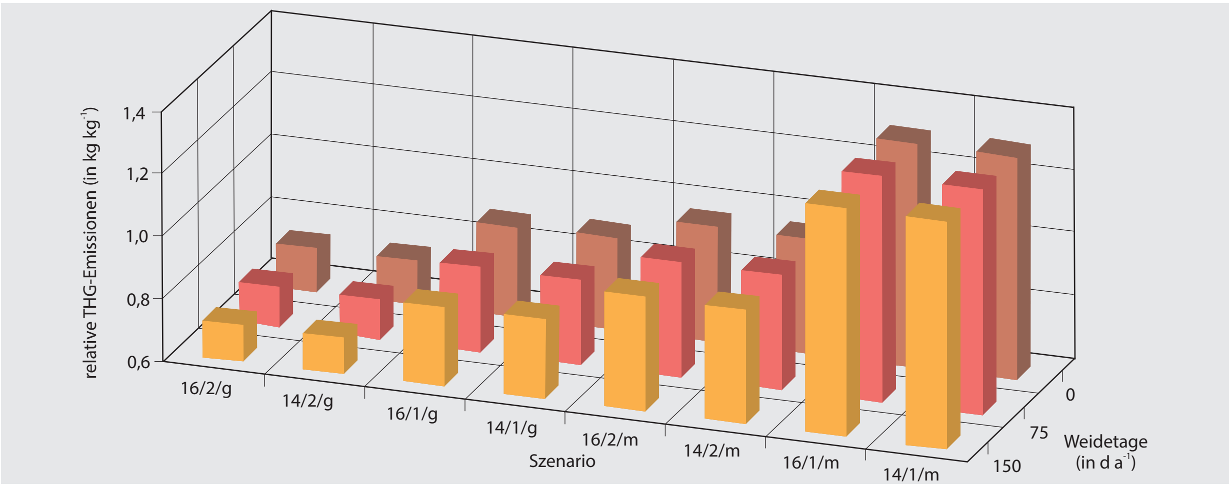

Abbildung 6
THG-Emissionen je kg verkaufte Milch in Abhängigkeit von Kraftfutterart und -menge, Grundfutterqualität sowie der Anzahl der Weidetage, Düngung nach geltender DüV (LWK-Nds, 2013). Zu Details siehe Tabellen A8 und A9 im Anhang.

Aus den Abbildungen 5 bis 7 und den Tabellen 5 und 7 lassen sich die folgenden Schlüsse ziehen:

- In allen Fällen führt vermehrter Weidegang *bei gleich bleibender Milchleistung* zu erhöhtem Energiebedarf (Bewegungsenergie), zu erhöhtem Futterbedarf und zu erhöhten absoluten CH_4-Emissionen aus der Verdauung.
- Der Vergleich der Abbildungen 1 und 5 zeigt, wie sehr die THG-Emissionen durch die Milchmenge bestimmt werden.
- Da die CH_4-Emissionen aus der auf der Weide ausgeschiedenen organischen Masse geringer sind als die der ins Lager gelangenden, sinken die CH_4-Emissionen aus dem Wirtschaftsdüngermanagement.
- Der Energiegehalt des Weidefutters ist jedoch höher als der des Stallfutters. Insgesamt sinkt daher der Futterbedarf der Tiere geringfügig (obwohl die Milchleistung bei gutem Futter geringfügig zunimmt).
- Entscheidenden Einfluss auf Milchleistung und Emissionen hat die Grundfutterqualität. Bei gleichen MLF-Gaben lassen sich die Emissionen durch gute Grundfutterqualität um etwa ein Drittel senken.
- Erhöhte Kraftfutteraufnahme hat erhöhte Milchleistungen zur Folge. Die Emissionen je Kuh steigen mit der Milchleistung. Die auf die Milchmenge bezogenen Emissionen sinken mit zunehmender Leistung deutlich, insbesondere mit zunehmender Kraftfuttermenge. Bemerkenswert ist, dass bei mäßiger Futterqualität und geringem Kraftfuttereinsatz die produktbezogenen Emissionen zunehmen, bei Verdoppelung der Kraftfuttermenge jedoch abnehmen, wenn die Zahl der Weidetage erhöht wird. Kraftfutter hat deutlich geringere CH_4-Emissionen aus der Verdauung je MJ NEL als das Grundfutter.
- MLF 14/3 und MLF 16/3 unterscheiden sich im Gegensatz zu den NH_3-Emissionen kaum hinsichtlich der THG-

Emissionen. Die Unterschiede sind auf veränderte N_2O-Mengen zurück zu führen.

- Verringerter Mineraldünger-Einsatz als Folge der Anwendung eines verbesserten Mineraldünger-Äquivalents für Wirtschaftsdünger äußert sich ebenfalls in Verringerungen der N_2O-Emissionen (verringerte N-Aufnahme und -Ausscheidung), aber auch beim Energieeinsatz bei der Mineraldünger-Herstellung. Zwischen der derzeit gültigen DüV und dem Entwurf 2015 sind Unterschiede in der Grafik nicht erkennbar.

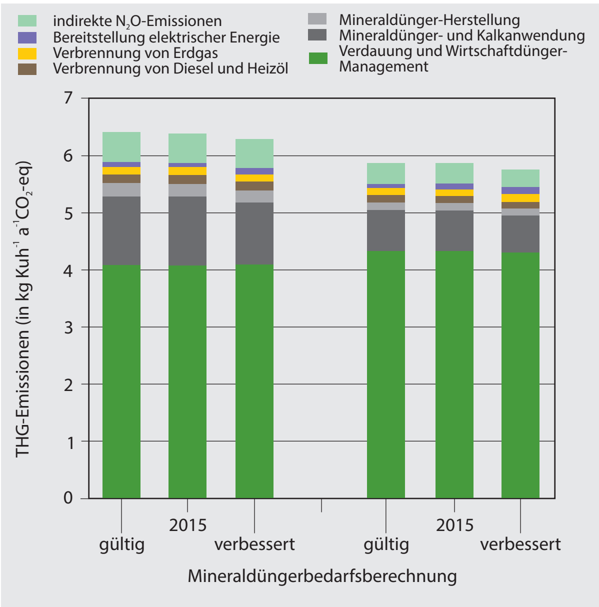

Abbildung 7
Einfluss der gewählten Mineraldüngeräquivalente (gültige DüV, Entwurf 2015 der DüV, verbesserte MDÄ) auf die THG-Emissionen (Szenarien 16/2/g150, links, und 16/2/m/150, rechts)

3.4 Flächenbedarf als Funktion der Fütterung

Landwirtschaftlich nutzbare Böden sind nicht vermehrbar. Ihr Schutz ist notwendige Aufgabe einer jeden Gesellschaft, völlig unabhängig von der volkwirtschaftlichen Bedeutung der Landwirtschaft. Der Flächenbedarf eines Produktionssystems ist deshalb eine wichtige Kenngröße. Die auf das Produkt bezogenen Flächen sind in Abbildungen 8 dargestellt.

Der Flächenbedarf ist primär vom Ertragsniveau und den erzeugten Grundfutterqualitäten abhängig. Es zeigt sich jedoch, dass bei hohen Erträgen und Qualitäten des erzeugten Grundfutters auf dem Grünland keine nennenswerte *weitere* Reduzierung des Flächenbedarfs für die Milcherzeugung mit zunehmender Kraftfuttersupplementierung verbunden sein muss (Tabelle A11, oben). Bei mäßiger Grundfutterqualität bewirkt zunehmender Weidegang eine Abnahme der auf Milch bezogenen Produktionsfläche (Abbildung 8). Zudem ist hier mit Zunahme der Kraftfuttersupplementierung in der Ration eine stärkere Abnahme des produktbezogenen Flächenbedarfs zu erkennen (Tabelle A12, unten).

4 Diskussion

4.1 Unsicherheiten

Der komplexe Modellansatz einschließlich der Eingangsparameter führt zu Unsicherheiten (95-%-Konfidenzintervallen), die für die Absolutbeträge der NH_3-Emissionen insgesamt in einer Größenordnung von ca. 20 %, für THG unter 40 % liegen dürften (Rechnungen des nationalen landwirtschaftlichen Emissionsinventars, Haenel et al., 2016). Die Höhe der Emissionen ist im Wesentlichen durch die Milchleistung bestimmt, von der fast alle anderen Ergebnisgrößen linear abhängen. D. h., dass die in den Rechnungen erzielten Ergebnisse im Trend auch dann zutreffend sind, wenn die absoluten Größen unsicher sind. So ist etwa die Unsicherheit der Versickerungsmengen erheblich, alle Szenarien werden

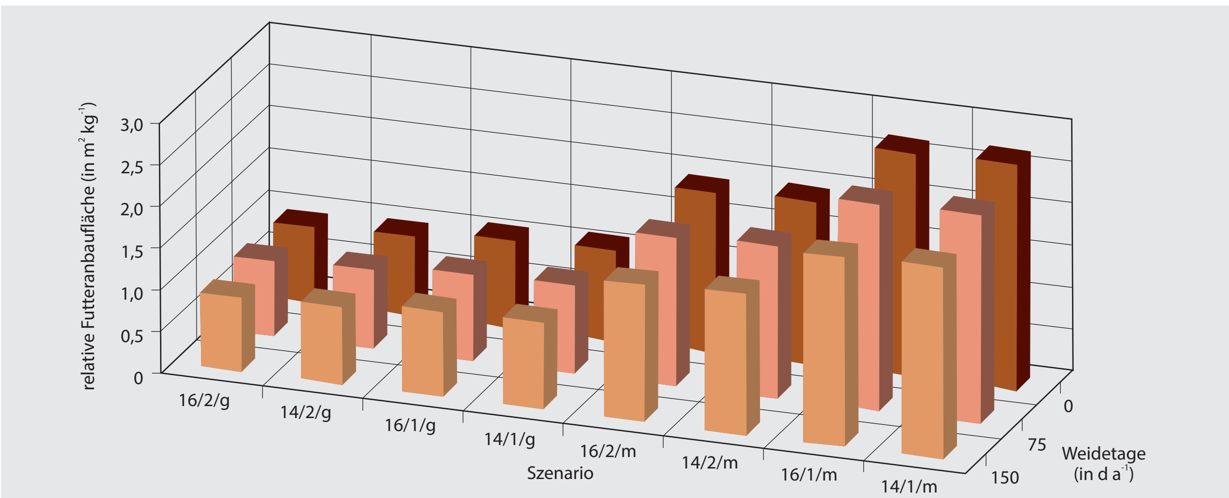

Abbildung 8
Flächenbedarf zur Futterproduktion je kg verkaufte Milch in Abhängigkeit von Kraftfutterart und -menge sowie der Anzahl der Weidetage. Details sind in den Tabellen A10 bis A12 aufgeführt.

jedoch mit dem gleichen Verfahren berechnet. Für die Bewertung der Unsicherheiten dieser Arbeit sind deshalb die sog. „Unsicherheiten der Trends", die für das nationale Emissionsinventar ebenfalls berechnet werden, von Bedeutung. Sie liegen für NH_3 bei nur etwa 4 %, für GHG bei 12 % (Haenel et al., 2016).

4.2 Repräsentativität

Die gasförmigen Emissionen in der Milcherzeugung sind von einer Vielzahl gleichzeitig wirkender Faktoren abhängig (z. B. Haltungssystem, Qualität der eingesetzten Grundfuttermittel, Verhältnis von Grund- und Kraftfutter in der Ration, Nutzungsdauer der Kühe, Exkrementenbehandlung, -lagerung und -ausbringung, Intensität der pflanzenbaulichen Maßnahmen, Art und Weise der Futterkonservierung und -lagerung, Düngungsintensität, Standort, etc.). Insbesondere die Höhe der Milchleistung und damit der Kraftfutteranteil in der Ration hat sowohl unter Stall- als auch Weidebedingungen einen entscheidenden Einfluss auf die produktbezogenen Emissionen (z. B. Dämmgen et al., 2009; 2016 a, b; Menzel et al., 2015; Haenel et al., 2016).

In der vorliegenden Arbeit werden Emissionen bei ganzjähriger Stallhaltung denen einer saisonalen Weidehaltung – jeweils bei einheitlich limitiertem Kraftfuttereinsatz – vergleichend gegenübergestellt. Das *Leistungsniveau* variiert zwischen ca. 4700 und 9000 kg Milch je Kuh und Jahr. Damit wird ein Leistungsspektrum berücksichtigt, das auch für die Praxis unter Weidebedingungen regelmäßig zu finden ist (Leisen und Rieger, 2007; Albers und Backes, 2012; Brade, 2012; Haenel et al., 2016).

Vergleichswerte für Emissionen sind vor allem der nationalen Emissionsberichterstattung zu entnehmen. Es ist dort jedoch unüblich, die gesamte Produktionskette zu betrachten. Die aufgeführten Emissionen der Einzelschritte entsprechen im Detail denen des nationalen Emissionsinventars. Insgesamt fügen sich die Ergebnisse in die in Dämmgen et al. (2016 a, b) erörterten ein und sind in der üblichen Größenordnung (z. B. Hirschfeld et al., 2008; Zollitsch et al, 2010; Zehetmeier und Heißenhuber, 2012; Brade, 2014).

Die Ergebnisse sind nicht übertragbar auf solche Produktionssysteme, die beispielsweise den Einsatz wesentlich höherer Kraftfutter- oder auch Maissilageanteile in der Ration voraussetzen.

4.3 Machbarkeit und Wirtschaftlichkeit

Internationale Vergleiche zeigen, dass Milch in unterschiedlicher Weise produziert werden kann:

- der „Hochleistungsansatz" mit vorzugsweise ganzjähriger Stallhaltung und hohem Kraftfuttereinsatz,
- der „weidebasierte Ansatz" mit konsequenter Nutzung von Dauergrünland und begrenztem Einsatz von Kraftfutter.

Beide Produktionsstrategien haben zum Ziel, die hohen Produktionskosten in der Milchproduktion zu senken (Brade, 2012). Kolver und Muller (1998) sowie Muller und Tozer (2005) weisen darauf hin, dass Holstein-Kühe bei optimaler Weidequalität und ausschließlicher Weidefütterung etwa 20 bis 26 kg Milch pro Tag produzieren können. Höhere Leistungen erfordern in der Regel eine Kraftfuttersupplementierung. Dabei lässt der leistungssteigernde Effekt der Supplementierung mit steigender Menge nach. Aktuelle Studien zeigen auf, dass auch in Deutschland bzw. in benachbarten europäischen Ländern eine wirtschaftliche Weidenutzung möglich ist, sofern die betrieblichen Gegebenheiten (ausreichend arrondierte Flächen, Einstellung des Betriebsleiters) und die Voraussetzungen des Standortes (Weidefähigkeit des Bodens, ausreichende Niederschläge) dazu passen (vgl. Doherty et al., 2004; Leisen und Rieger, 2007; Kiefer und Bahrs, 2015). Dennoch ist aus ökonomischer Sicht eine Rückkehr zur von vielen Vermarktern und Verbrauchern erwünschten Weidehaltung oftmals nur bei zusätzlichen finanziellen Anreizen (insbesondere Preiszuschläge für ‚Weidemilch') zu erwarten. Jüngste Befragungen in den Niederlanden zeigten, dass mehr als zwei Drittel der niederländischen Verbraucher bereit sind, für Molkereiprodukte aus Milch von Kühen mit Weidegang mehr Geld auszugeben (Milieudefensie, 2015). Demnach würden 35 % der Befragten einen Preisaufschlag von 1 Cent bis 5 Cent je Liter Milch von Kühen akzeptieren, die mindestens 120 Tage im Jahr jeweils sechs Stunden auf der Weide verbringen. Eine Bewertung von Weidehaltungssystemen aus Sicht von Landwirten und Ausgestaltung eines Weidemilchprogramms mit Ermittlung von dafür nötigen Preisaufschlägen auf den Milchpreis ist Gegenstand eines von der Arbeitsgemeinschaft deutscher Rinderzüchter (ADR) initiierten Forschungsvorhabens (Zühlsdorf et al., 2014).

Die vorliegende Arbeit zeigt, dass auch aus Gründen der Minderung gasförmiger Emissionen Weidegang immer dann berechtigt erscheint, wenn dazu die natürlichen und betrieblichen Voraussetzungen gegeben sind.

4.4 Resumé

Grünlandbewirtschaftung nach guter fachlicher Praxis in Stallnähe und mit begrenztem Kraftfuttereinsatz bietet die Möglichkeit einer tiergerechten Haltung von Milchrindern, die gleichzeitig zur Reduzierung gasförmiger Emissionen, vor allem der NH_3-Emissionen, im Vergleich zur ganzjährigen Stallhaltung (bei gleichen Randbedingungen) genutzt werden kann. Einer guten Grundfutterqualität kommt bei der Minderung der THG-Emissionen eine große Bedeutung zu.

Genügend hohe Leistungen auf Grünlandstandorten erfordern jedoch auch eine gezielte Supplementierung von Kraftfutter in der Ration. Diese Zufütterung erweist sich aus der Blickrichtung der Flächenproduktivität (Gesamtflächenbedarf in $m^2\ kg^{-1}$ Milch) vor allem dann vorteilhaft, wenn die Erträge und Qualitäten des auf dem Grünland erzeugten Grundfutters nur mäßig sind.

Danksagung

Wir danken Herrn Dr. Küster (LWK Niedersachsen, Northeim), der uns hinsichtlich der Zusammensetzung von praxisüblichem Milchleistungsfutter aus heimischen Futtermitteln beraten hat.

Tabellenanhang

Tabelle A1

Milchleistungen in kg Kuh^{-1} a^{-1} bei guter (oben) und mäßiger (unten) Grundfutterqualität

	Weidetage (in d a^{-1})		
Szenario	0	75	150
14/1/g	6347	6455	6518
14/2/g	8304	8379	8457
16/1/g	6386	6448	6512
16/2/g	8284	8359	8436
14/1/m	4095	4016	3937
14/2/m	6009	5930	5851
16/1/m	4088	4010	3931
16/2/m	5993	5914	5835

Tabelle A2

NH_3-Emissionen in kg Kuh^{-1} a^{-1} bei guter Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/g (LWK-Nds, 2013)	58,8	55,5	52,2
14/2/g (LWK-Nds, 2013)	57,6	54,3	51,5
16/1/g (LWK-Nds, 2013)	59,6	56,3	53,0
16/2/g (LWK-Nds, 2013)	59,9	56,6	53,2
14/1/g (BMEL, 2015)	58,1	55,1	52,1
14/2/g (BMEL, 2015)	56,8	53,8	51,3
16/1/g (BMEL, 2015)	58,9	55,9	52,8
16/2/g (BMEL, 2015)	59,0	56,1	53,0
14/1/g (verbessert)	57,3	54,0	50,6
14/2/g (verbessert)	56,0	52,7	49,8
16/1/g (verbessert)	58,1	54,8	51,3
16/2/g (verbessert)	58,2	54,9	51,4

Tabelle A3

NH_3-Emissionen in kg Kuh^{-1} a^{-1} bei mäßiger Grundfutterqualität, Düngung geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/m (LWK-Nds, 2013)	42,9	39,3	35,7
14/2/m (LWK-Nds, 2013	42,8	39,3	35,8
16/1/m (LWK-Nds, 2013)	43,8	40,1	36,4
16/2/m (LWK-Nds, 2013)	45,1	41,3	37,6
14/1/m (BMEL, 2015)	42,3	38,9	35,6
14/2/m (BMEL, 2015)	42,1	38,8	35,6
16/1/m (BMEL, 2015)	43,3	39,7	36,3
16/2/m (BMEL, 2015)	44,4	40,9	37,4
14/1/m (verbessert)	41,8	38,1	34,4
14/2/m (verbessert)	41,5	37,9	34,4
16/1/m (verbessert)	42,7	38,9	35,1
16/2/m (verbessert)	43,7	39,9	36,2

Tabelle A4

Auf vermarktbare Milch bezogene NH_3-Emissionen in g kg^{-1} bei guter Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/g (LWK-Nds, 2013)	9,45	8,78	8,18
14/2/g (LWK-Nds, 2013)	7,08	6,62	6,22
16/1/g (LWK-Nds, 2013)	9,52	8,91	8,30
16/2/g (LWK-Nds, 2013)	7,37	6,91	6,44
14/1/g (BMEL, 2015)	9,33	8,71	8,15
14/2/g (BMEL, 2015)	6,98	6,55	6,19
16/1/g (BMEL, 2015)	9,41	8,84	8,27
16/2/g (BMEL, 2015)	7,27	6,85	6,41
14/1/g (verbessert)	9,22	8,54	7,93
14/2/g (verbessert)	6,88	6,41	6,01
16/1/g (verbessert)	9,29	8,67	8,05
16/2/g (verbessert)	7,17	6,70	6,22

Tabelle A5

Auf vermarktbare Milch bezogene NH_3-Emissionen in g kg^{-1} bei mäßiger Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/m (LWK-Nds, 2013)	10,70	9,98	9,25
14/2/m (LWK-Nds, 2013)	7,27	6,75	6,24
16/1/m (LWK-Nds, 2013)	10,94	10,20	9,45
16/2/m (LWK-Nds, 2013)	7,67	7,12	6,57
14/1/m (BMEL, 2015)	10,55	9,89	9,22
14/2/m (BMEL, 2015)	7,15	6,68	6,21
16/1/m (BMEL, 2015)	10,79	10,11	9,42
16/2/m (BMEL, 2015)	7,56	7,05	6,54
14/1/m (verbessert)	10,41	9,67	8,93
14/2/m (verbessert)	7,04	6,52	6,00
16/1/m (verbessert)	10,65	9,89	9,12
16/2/m (verbessert)	7,44	6,88	6,32

Tabelle A6

THG-Emissionen in Mg Kuh^{-1} a^{-1} CO_2-eq bei guter Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/g (LWK-Nds, 2013)	6,08	6,00	5,94
14/2/g (LWK-Nds, 2013)	6,55	6,48	6,42
16/1/g (LWK-Nds, 2013)	6,07	6,00	5,93
16/2/g (LWK-Nds, 2013)	6,54	6,48	6,41
14/1/g (BMEL, 2015)	6,02	5,97	5,92
14/2/g (BMEL, 2015)	6,48	6,44	6,40
16/1/g (BMEL, 2015)	6,01	5,96	5,92
16/2/g (BMEL, 2015)	6,47	6,43	6,39
14/1/g (verbessert)	5,96	5,88	5,80
14/2/g (verbessert)	6,42	6,35	6,28
16/1/g (verbessert)	5,95	5,87	5,80
16/2/g (verbessert)	6,41	6,33	6,26

Tabelle A7

THG-Emissionen in Mg Kuh^{-1} a^{-1} CO_2-eq bei mäßiger Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/m (LWK-Nds, 2013)	5,60	5,51	5,42
14/2/m (LWK-Nds, 2013)	6,05	5,96	5,86
16/1/m (LWK-Nds, 2013)	5,60	5,51	5,42
16/2/m (LWK-Nds, 2013)	6,05	5,95	5,85
14/1/m (BMEL, 2015)	5,55	5,48	5,41
14/2/m (BMEL, 2015)	6,00	5,92	5,85
16/1/m (BMEL, 2015)	5,55	5,48	5,40
16/2/m (BMEL, 2015)	5,99	5,92	5,84
14/1/m (verbessert)	5,50	5,41	5,32
14/2/m (verbessert)	5,94	5,85	5,75
16/1/m (verbessert)	5,50	5,40	5,31
16/2/m (verbessert)	5,94	5,84	5,74

Tabelle A8

Auf vermarktbare Milch bezogene THG-Emissionen in kg kg^{-1} CO_2-eq bei guter Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1}]		
Futter (Berechnungsverfahren)	0	75	150
14/1/g (LWK-Nds, 2013)	0,893	0,869	0,852
14/2/g (LWK-Nds, 2013)	0,739	0,726	0,712
16/1/g (LWK-Nds, 2013)	0,886	0,869	0,852
16/2/g (LWK-Nds, 2013)	0,740	0,726	0,713
14/1/g (BMEL, 2015)	0,885	0,864	0,850
14/2/g (BMEL, 2015)	0,732	0,721	0,711
16/1/g (BMEL, 2015)	0,878	0,864	0,850
16/2/g (BMEL, 2015)	0,732	0,722	0,711
14/1/g (verbessert)	0,877	0,852	0,834
14/2/g (verbessert)	0,725	0,711	0,698
16/1/g (verbessert)	0,870	0,852	0,834
16/2/g (verbessert)	0,725	0,711	0,697

Tabelle A9

Auf vermarktbare Milch bezogene THG-Emissionen in kg kg^{-1} CO_2-eq bei mäßiger Grundfutterqualität, Düngung nach geltender DüV (LWK-Nds, 2013, oben), dem Entwurf der DüV (BMEL, 2015, Mitte) sowie mit verbesserter Anrechnung der N-Einträge mit dem Wirtschaftsdünger (unten)

	Weidetage (in d a^{-1})		
Futter (Berechnungsverfahren)	0	75	150
14/1/m (LWK-Nds, 2013)	1,309	1,317	1,325
14/2/m (LWK-Nds, 2013)	0,965	0,965	0,964
16/1/m (LWK-Nds, 2013)	1,311	1,318	1,326
16/2/m (LWK-Nds, 2013)	0,967	0,966	0,965
14/1/m (BMEL, 2015)	1,299	1,310	1,322
14/2/m (BMEL, 2015)	0,957	0,960	0,962
16/1/m (BMEL, 2015)	1,300	1,311	1,323
16/2/m (BMEL, 2015)	0,959	0,961	0,963
14/1/m (verbessert)	1,289	1,295	1,302
14/2/m (verbessert)	0,950	0,949	0,947
16/1/m (verbessert)	1,290	1,296	1,302
16/2/m (verbessert)	0,951	0,949	0,948

Tabelle A10

Flächenbedarf zur Bereitstellung von Kraftfutter in ha Kuh^{-1}

	Weidetage (in d a^{-1}]		
Futter	0	75	150
14/1/g, 14/1/m	0,082	0,082	0,082
14/2/g, 14/2/m	0,203	0,203	0,203
16/1/g, 16/1/m	0,069	0,069	0,069
16/2/g, 16/2/m	0,171	0,171	0,171

Tabelle A11

Flächenbedarf zur Bereitstellung von Grundfutter in ha Kuh^{-1}, gute Futterqualität (oben), mäßige Futterqualität (unten)

	Weidetage (in d a^{-1})		
Futter	0	75	150
14/1/g	0,588	0,584	0,581
14/2/g	0,564	0,561	0,559
16/1/g	0,588	0,584	0,581
16/2/g	0,563	0,561	0,559
14/1/m	0,504	0,497	0,490
14/2/m	0,477	0,470	0,464
16/1/m	0,504	0,497	0,490
16/2/m	0,477	0,470	0,464

Tabelle A12

Auf vermarktbare Milch bezogener Flächenbedarf (Kraft- und Grundfutter) in m^2 kg^{-1}, gute Futterqualität (oben), mäßige Futterqualität (unten)

	Weidetage (in d a^{-1})		
Futter	0	75	150
14/1/g	1,076	1,053	1,037
14/2/g	0,942	0,931	0,920
16/1/g	1,049	1,034	1,018
16/2/g	0,905	0,894	0,883
14/1/m	2,715	2,507	2,290
14/2/m	1,965	1,824	1,679
16/1/m	2,687	2,478	2,261
16/2/m	1,916	1,774	1,628

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Landbauforschung
Applied Agricultural and Forestry Research

Vol. 66

No. 3· 09.2016

Herausgeber · *Editor*
Johann Heinrich von Thünen-Institut
Bundesallee 50
38116 Braunschweig
Germany

Preis · Price 8 €

ISSN 0458-6859