U. Dämmgen, W. Brade, U. Meyer, H.-D. Haenel, C. Rösemann, H. Flessa, J. Webb, M. Strogies, M. Schwerin · **Landbauforsch**
Appl Agric Forestry Res · 3 2016 (66)161-192
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

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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.

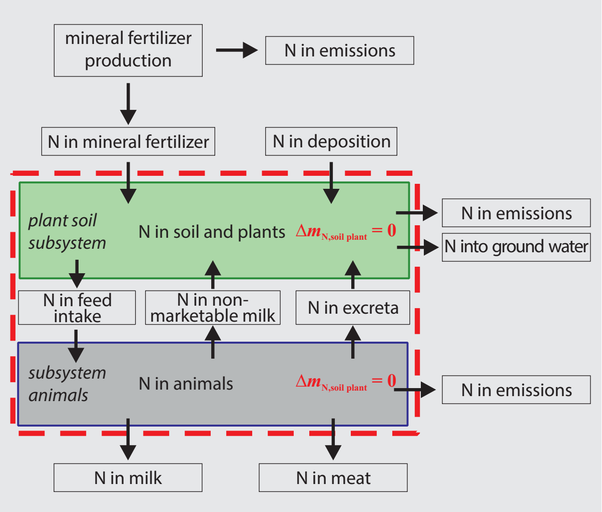

Figure 1

N flows in the system "herd" (red broken frame) und the subsystems "plant soil" and "animals"

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.

Table 1

Example animal losses in dairy herds

	overall losses (slaughtered and perished animals)	share of utilized animals (slaughtered animals) ******
	x_{loss}	x_{util}
	animal animal^{-1}	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.

2.2.1.1 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:

$$N_{\mathrm{cow}} = N_{\mathrm{cow,1}} + N_{\mathrm{cow,2}} + N_{\mathrm{cow,3}} \tag{1}$$

where

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

The numbers in the three lactations are obtained as:

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

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

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[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).

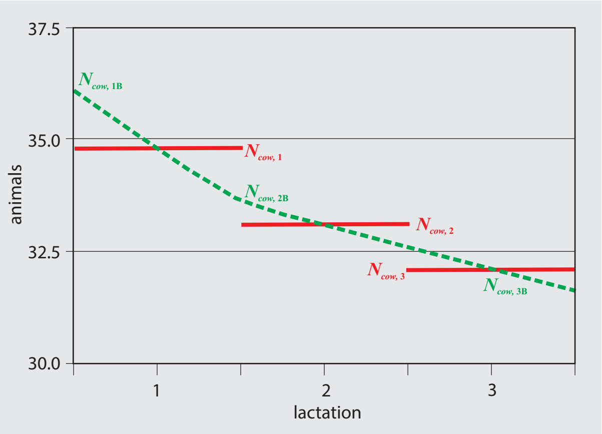

Figure 2

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.

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

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

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

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:

$$N_{\text{util, cow},1} = N_{\text{cow 1}} \cdot x_{\text{loss, cow},1} \cdot x_{\text{util}} \tag{4}$$

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 ($x_{\text{util}} = 0.92$ 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:

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

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 ($x_{\text{C}} = 0.98$ calf cow^{-1})

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

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

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

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

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:

$$N_{\text{calf}} = \frac{N_{\text{calf, B}} + N_{\text{calf, E}}}{2} \tag{7}$$

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:

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

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:

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

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:

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

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:

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

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:

$$N_{\text{BH}} = \frac{N_{\text{BH, B}} + N_{\text{BH, E}}}{2} \tag{12}$$

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})

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[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.

$N_{\text{BH, B}}$	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:

$$N_{\text{BB, A}} = N_{\text{Mcalf, E}} \tag{13}$$

where

$N_{\text{BB, A}}$	number of beef bulls at the beginning of the fattening period (in Bbull herd^{-1} lactation^{-1})
$N_{\text{Mcalf, E}}$	number of surviving male calves (in calf herd^{-1} lactation^{-1})

For protein production the following number can be used:

$$N_{\text{BMB, E}} = N_{\text{BB, A}} \cdot \left(1 - x_{\text{loss, BB}}\right) \tag{14}$$

where

$N_{\text{BB, E}}$	number of beef bulls at the end of the fattening period (in Bbull herd^{-1} lactation^{-1})
$N_{\text{BB, B}}$	number of beef bulls at the beginning of the fattening period (in Bbull herd^{-1} lactation^{-1})
$x_{\text{loss, BB}}$	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:

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

where

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

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

where

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

The amount fed to calves is:

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

where

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

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

where

$\Delta Y_{\text{depr, n}}$	yield reduction caused by mastitis and other illnesses in n-th lactation (in Mg herd^{-1} lactation^{-1})
$Y_{\text{milk, n}}$	nominal milk yield in n-th lactation (in Mg herd^{-1} lactation^{-1})
$I_{\text{sick, n}}$	incidence for mastitis and other illnesses in n-th lactation (in cow cow^{-1})
$x_{\text{depr, 1}}$	yield depression related to incidences in n-th lactation (in kg kg^{-1})
$X_{\text{depr, n}}$	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) $I_{\text{sick, n}}$ cow cow^{-1}	relative yield depression* $X_{\text{depr, n}}$ kg kg^{-1}	fraction of cows whose treatment results in non-marketable milk ** ½ $I_{\text{sick, n}}$ cow cow^{-1}	fraction of non-marketable milk $X_{\text{milk, dis, n}}$ 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

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

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

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:

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

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:

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

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

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).

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.

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

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 $x_{\text{w, j}} = 0$ 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

	overall losses *	losses during emptying
feed	kg kg^{-1} DM	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:

$$M_{\text{SG, j}} = d_{\text{SG, j}} \cdot TGW_{\text{j}} \cdot \gamma_1 \cdot \gamma_2 \cdot \eta \tag{24}$$

where

$M_{\text{SG, j}}$	fraction of harvest crop used as seeding material (in Mg ha^{-1} a^{-1} FM)
$d_{\text{SG, j}}$	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 ($\gamma_1 = 1 \cdot 10^{-3}$ kg kg^{-1})
γ_2	conversion factor for mass units ($\gamma_2 = 1 \cdot 10^{-3}$ Mg kg^{-1})
η	conversion factor for area units ($\eta = 10000$ 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			sowing density			mass of seeds required
	kg (1000 grain)$^{-1}$			grain m^{-2}			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.

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[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) * $Mg\ ha^{-1}\ a^{-1}$	DM content $kg\ kg^{-1}$	mean yield (DM) $Mg\ ha^{-1}\ a^{-1}$	fertilizer N ** $kg\ ha^{-1}\ a^{-1}$	lime*** $Mg\ ha^{-1}\ a^{-1}$
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.

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

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 $X_{\text{FB, j}}$ $kg\ kg^{-1}$	GE content crop $\eta_{\text{GE, F, j}}$ $MJ\ kg^{-1}$	GE content feed constituent $\eta_{\text{GE, FB, j}}$ $MJ\ kg^{-1}$	allocation factor $f_{\text{all, j}}$ $kg\ kg^{-1}\ MJ\ MJ^{-1}$
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:

$$M_{\mathrm{NMF}} = \left(\begin{array}{l} \sum M_{\mathrm{F,N,j}} - M_{\mathrm{NMa}} \cdot f_{\mathrm{MFE}} \\ + \left(M_{\mathrm{AD}} + M_{\mathrm{DEx}}^{*} \right) \cdot \sum A_{\mathrm{j}} \end{array} \right) \cdot \gamma_{\mathrm{F}} \qquad (28)$$

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:

$$M_{\mathrm{F,N,j}} = \frac{B_{\mathrm{j}}}{x_{\mathrm{DM,j}} \cdot Y_{\mathrm{j}}} \cdot M_{\mathrm{E,j}} \qquad (29)$$

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

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

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.

$$M_{AD} = \sum M_{AD,j} \tag{31}$$

$$M_{AD,j} = M_{AD,r} \cdot A_j \cdot x_{AD,j} \tag{32}$$

where

M_{AD}	atmospheric N deposition (in kg $herd^{-1}$ a^{-1})
$M_{AD,j}$	atmospheric N deposition for a crop j (in kg $herd^{-1}$ a^{-1})
$M_{AD,r}$	mean regional deposition to short vegetation (in kg ha^{-1} a^{-1})
A_j	area cultivated for crop j (in ha $herd^{-1}$ $lactation^{-1}$)
$x_{AD,j}$	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	$EF_{NH3,MF,k}$ 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:

$$E_{NH3,MF} = \sum E_{NH3,MF,k} \tag{33}$$

$$\begin{aligned} E_{NH3,MF,k} &= EF_{NH3,MF,k} \cdot M_{MF,k} \cdot \gamma_{NH3} \\ &= EF_{NH3,MF,k} \cdot M_{MF} \cdot x_{MF,k} \cdot \gamma_{NH3} \end{aligned} \tag{34}$$

where

$E_{NH3,MF}$	overall NH_3 emissions from mineral fertilizer application (in kg $herd^{-1}$ $lactation^{-1}$ NH_3)
$E_{NH3,MF,k}$	NH_3 emissions from application of fertilizer k (in kg $herd^{-1}$ $lactation^{-1}$ NH_3)
$EF_{NH3,MF,k}$	emission factor for mineral fertilizer k (in kg NH_3 (kg N)$^{-1}$)
$M_{MF,k}$	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)
$x_{MF,k}$	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.

$$E_{NO,MF} = EF_{NO,MF} \cdot \gamma_{NO} \cdot \sum_{k=1}^{n} M_{MF,k} \tag{35}$$

where

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

$$E_{N2O,MF} = EF_{N2O,MF} \cdot \gamma_{N2O} \cdot \sum_{k=1}^{n} M_{MF,k} \tag{36}$$

where

$E_{N2O,MF}$	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:

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

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: $EF_{NO\text{-}N, Ma} = 0.1\ EF_{N2O\text{-}N, Ma}$; $EF_{N2, Ma} = 3\ EF_{N2O\text{-}N, Ma}$).

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).

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

$$E_{CO2, Slime} = \left(x_{calcite} \cdot EF_{CO2, calcite} + x_{magnesite} \cdot EF_{CO2, magnesite} \right) \cdot M_{Slime} = EF_{CO2, Slime} \cdot M_{Slime} \qquad (38)$$

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:

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

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).

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

where

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

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

where

$E_{\mathrm{N2O,\,CR}}$	N_2O emissions from crop residues (in kg herd^{-1} lactation^{-1} N_2O)
$EF_{\mathrm{N2O,\,CR}}$	N_2O emission factor for crop residues ($EF_{\mathrm{N2O,\,CR}}$ = 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

$$M_{\mathrm{CR}} = \sum_j A_{\mathrm{j}} \cdot x_{\mathrm{renew,\,j}} \cdot x_{\mathrm{mov,\,j}} \cdot Y_{\mathrm{j}} \cdot \left(x_{\mathrm{Y,\,DM,\,j}} + a_{\mathrm{above,\,j}} \cdot x_{\mathrm{DM,\,below,\,j}}\right) \cdot a_{\mathrm{below}} \cdot x_{\mathrm{N,\,below}} \qquad (42)$$

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})
$x_{\mathrm{renew,\,j}}$	share of the crop j that is harvested annually (in ha ha^{-1})
$x_{\mathrm{mow,\,j}}$	1 / number of harvests of crop j per year (dimensionless)
Y_{j}	yield of crop j (FM) (in Mg ha^{-1})
$x_{\mathrm{Y,\,DM,\,j}}$	dry matter content of crop j (in kg kg^{-1})
$a_{\mathrm{above,\,j}}$	share of above ground plant residues related to amount harvested (in kg kg^{-1})
$x_{\mathrm{DM,\,above,\,j}}$	dry matter content of above ground parts of crop j (in kg kg^{-1})
$a_{\mathrm{below,\,j}}$	share of below ground plant residues related to the amount harvested (in kg kg^{-1})
$x_{\mathrm{N,\,below,\,j}}$	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}	x_{mow}	$x_{\mathrm{Y,\,DM,\,j}}$	$x_{\mathrm{AGR,\,DM,\,j}}$	$a_{\mathrm{above,\,j}}$	$x_{\mathrm{N,\,above,\,j}}$	$a_{\mathrm{below,\,j}}$	$x_{\mathrm{N,\,below,\,j}}$
	ha ha^{-1}		kg kg-1	kg kg^{-1}	kg kg^{-1}	kg kg^{-1} N	kg kg^{-1}	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:

$$E_{\mathrm{NH3,\,CAN}} = EF_{\mathrm{NH3,\,CAN}} \cdot M_{\mathrm{NH4\text{-}N,\,CAN}} \cdot \gamma_{\mathrm{NH3}} \tag{43}$$

$$E_{\mathrm{NH4\text{-}N,\,CAN}} = EF_{\mathrm{NH4\text{-}N,\,CAN}} \cdot M_{\mathrm{NH4\text{-}N,\,CAN}} \tag{44}$$

$$E_{\mathrm{NO3\text{-}N,\,CAN}} = EF_{\mathrm{NO3\text{-}N,\,CAN}} \cdot M_{\mathrm{NO3\text{-}N,\,CAN}} \tag{45}$$

where

$E_{\mathrm{NH3,\,CAN}}$	gaseous NH_3 emission from CAN production (in kg $herd^{-1}$ $lactation^{-1}$)
$EF_{\mathrm{NH3,\,CAN}}$	NH_3 emission factor for CAN production ($EF_{\mathrm{NH3,\,CAN}}$ = 0.030 kg kg^{-1})
$M_{\mathrm{NH4\text{-}N,\,CAN}}$	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 $kmol^{-1}$)
$E_{\mathrm{NH4\text{-}N,\,CAN}}$	particulate NH_4-N emission from CAN production (in kg $herd^{-1}$ $lactation^{-1}$)
$EF_{\mathrm{NH4\text{-}N,\,CAN}}$	emission factor for particulate NH_4-N for CAN production ($EF_{\mathrm{NH4\text{-}N,\,CAN}}$ = 0.035 kg kg^{-1})
$E_{\mathrm{NO3\text{-}N,\,CAN}}$	particulate NO_3-N emission from CAN production (in kg $herd^{-1}$ $lactation^{-1}$)
$EF_{\mathrm{NO3\text{-}N,\,CAN}}$	emission factor for particulate NO_3-N for CAN production ($EF_{\mathrm{NO3\text{-}N,\,CAN}}$ = 0.035 kg kg^{-1})
$M_{\mathrm{NO3\text{-}N,\,CAN}}$	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:

$$M_{\mathrm{NO3\text{-}N,\,CAN}} = M_{\mathrm{NH4\text{-}N,\,CAN}} = \frac{1}{2} M_{\mathrm{N,\,CAN}} \tag{46}$$

where

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

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

where

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

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

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

where

$M_{\mathrm{HNO3\text{-}N}}$	amount of N in HNO_3 for AN synthesis (in kg $herd^{-1}$ $lactation^{-1}$)
$M_{\mathrm{AN\text{-}N}}$	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 ($EF_{\text{NO2}} = 0.010$ kg kg^{-1} related to HNO_3)

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

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 ($EF_{\text{NO2}} = 0.010$ kg kg^{-1}, related to HNO_3)
γ_{HNO3}	stoichiometric conversion factor ($\gamma_{\text{HNO3}} = 63/14$ kg kg^{-1} kmol kmol^{-1})
γ_{NO2}	stoichiometric conversion factor ($\gamma_{\text{NO2}} = 46/14$ 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:

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

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})

$$E_{\text{GHG, DAP}} = M_{\text{DAP}} \cdot EF_{\text{GHG, DAP}} \tag{51}$$

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:

$$E_{\text{GHG, P2O5, j}} = A_{\text{j}} \cdot M_{\text{PKF}} \cdot x_{\text{P2O5}} \cdot EF_{\text{P2O5}} \tag{52}$$

$$E_{\text{GHG, K2O, j}} = A_{\text{j}} \cdot M_{\text{PKF}} \cdot x_{\text{K2O}} \cdot EF_{\text{K2O}} \tag{53}$$

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 ($EF_{\text{P2O5}} = 0.56$ 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 ($EF_{\text{K2O}} = 0.43$ 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).

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[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):

$$E_{\mathrm{CO2,\,DF}} = \sum E_{\mathrm{CO2,\,DF,\,j}} \tag{54}$$

$$E_{\mathrm{CO2,\,DF,\,j}} = EF_{\mathrm{CO2,\,DF}} \cdot A_{\mathrm{j}} \cdot V_{\mathrm{DF,\,j}} \cdot \eta_{\mathrm{E,\,DF}} \cdot \rho_{\mathrm{DF}} \cdot \beta \tag{55}$$

where

$E_{\mathrm{CO2,\,DF}}$	CO_2 emissions from diesel fuel combustion (in kg herd^{-1} lactation^{-1} CO_2)
$E_{\mathrm{CO2,\,DF,\,j}}$	CO_2 emissions from fuel combustion for the production of crop j (in kg herd^{-1} lactation^{-1} CO_2)
$EF_{\mathrm{CO2,\,DF}}$	CO_2 emission factor for diesel fuel combustion ($EF_{\mathrm{CO2,\,DF}}$ = 74.1 kg GJ^{-1})
A_{j}	area cultivated for crop j (in ha herd^{-1} lactation^{-1})
$V_{\mathrm{DF,\,j}}$	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})
$\eta_{\mathrm{E,\,DF}}$	calorific value of diesel fuel ($\eta_{\mathrm{E,\,DF}}$ = 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:

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

$$E_{\mathrm{NH3\text{-}N,\,DF}} = \sum M_{\mathrm{DF,\,j}} \cdot EF_{\mathrm{NH3,\,DF}} \cdot \gamma_{\mathrm{NH3}} \tag{56}$$

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

where

$E_{\mathrm{NH3\text{-}N,\,DF}}$	NH_3-N emission from diesel fuel combustion (in Mg herd^{-1} lactation^{-1})
$M_{\mathrm{DF,\,j}}$	amount of diesel fuel used for the production of crop j (in kg ha^{-1})
$EF_{\mathrm{NH3,\,DF}}$	NH_3 emission factor for diesel fuel combustion ($EF_{\mathrm{NH3,\,DF}}$ = 8 g Mg^{-1})
γ_{NH3}	stoichiometric factor for NH_3-N emissions (γ_{NH3} = 14/17 kg kg^{-1} kmol kmol^{-1})
$E_{\mathrm{NOx\text{-}N,\,DF}}$	NO_x-N emission from diesel fuel combustion (in Mg herd^{-1} lactation^{-1})
$EF_{\mathrm{NOx,\,DF}}$	NO_x emission factor for diesel fuel combustion ($EF_{\mathrm{NOx,\,DF}}$ = 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
equivalent to	0.0241	MJ MJ^{-1}	seed						
	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:

$$E_{\mathrm{CO2,\,NG}} = EV_{\mathrm{CO2,\,NG}} \cdot EF_{\mathrm{CO2,\,NG}} \tag{58}$$

where

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

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

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.

$$M_{\mathrm{Wt,\,DC}} = \alpha \cdot \delta \cdot \left(a + b \cdot t + c \cdot Y_{\mathrm{M}} + d \cdot w_{\mathrm{DC}} + e \cdot m_{\mathrm{Na}}\right) \tag{59}$$

where

$M_{\mathrm{Wt,\,DC}}$	annual drinking water requirements of a dairy cow (in m^3 cow^{-1} a^{-1})
α	conversion factor for time units ($\alpha = 365$ d a^{-1})
δ	conversion factor for units of volume ($\delta = 1/1000$ 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) ($r^2 = 0.998$):

$$m_{\mathrm{Na}} = f + g \cdot Y_{\mathrm{M}} \tag{60}$$

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.

$$M_{\mathrm{Wt,\,He}} = \theta_{\mathrm{He}} \cdot \delta \cdot \left(h + l \cdot w_{\mathrm{He}}\right) \tag{61}$$

where

$M_{\mathrm{Wt,\,He}}$	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 ($\delta = 1/1000$ 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.

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

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):

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

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 %.

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

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.

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[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$_2$O 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.

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

where

$E_{\mathrm{N2O,\,AD}}$	indirect N$_2$O emissions from atmospheric deposition (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NH3\text{-}N,\,MaM}}$	NH$_3$-N emissions from manure management (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NO\text{-}N,\,MaM}}$	NO-N emissions from manure management (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NH3\text{-}N,\,graz}}$	NH$_3$-N emissions during grazing (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NO\text{-}N,\,graz}}$	NO-N emissions during grazing (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NH3\text{-}N,\,MF}}$	NH$_3$-N emissions from application of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NO\text{-}N,\,MF}}$	NO-N emissions from application of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NH3\text{-}N,\,MP}}$	NH$_3$-N emissions from the production of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NO\text{-}N,\,MP}}$	NO-N emissions from the production of mineral fertilizers (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NH3\text{-}N,\,DE}}$	NH$_3$-N emissions from the use of diesel engines and CH$_4$ fired boilers (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{NO\text{-}N,\,DE}}$	NO-N emissions from the use of diesel engines and CH$_4$ fired boilers (in kg herd^{-1} lactation^{-1})
$EF_{\mathrm{N2O,\,AD}}$	emission factor for indirect N$_2$O from atmospheric depositions ($EF_{\mathrm{N2O,\,Dep}} = 0.010$ kg kg^{-1} N)
γ_{N2O}	stoichiometric conversion factor ($\gamma_{\mathrm{N2O}} = 44/28$ kg kg^{-1} kmol kmol^{-1})

$$E_{\mathrm{N2O,\,leach}} = M_{\mathrm{N,\,soil}} \cdot x_{\mathrm{leach}} \cdot EF_{\mathrm{N2O,\,leach}} \cdot \gamma_{\mathrm{N2O}} \tag{65}$$

and:

$$M_{\mathrm{N,\,soil}} = M_{\mathrm{N,\,MaM}} + M_{\mathrm{N,\,graz}} + M_{\mathrm{N,\,MF}} + M_{\mathrm{N,\,CR}} \tag{66}$$

where

$E_{\mathrm{N2O,\,leach}}$	indirect N$_2$O emission from run-off and leaching (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,soil}}$	N available in soil (in kg herd^{-1} lactation^{-1})
x_{leach}	fraction of N leached ($x_{\mathrm{leach}} = 0.30$ kg kg^{-1})
$EF_{\mathrm{N2O,\,leach}}$	emission factor for N$_2$O from leached N ($EF_{\mathrm{N2O,\,leach}} = 0.0075$ kg kg^{-1} N)
γ_{N2O}	stoichiometric conversion factor ($\gamma_{\mathrm{N2O}} = 44/28$ kg kg^{-1} kmol kmol^{-1})
$M_{\mathrm{N,\,MaM}}$	N input into soil from manure management (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,graz}}$	N input into soil during grazing (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,MF}}$	N input into soil with mineral fertilizers (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,CR}}$	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).

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

where

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

$M_{\mathrm{N,\,AD}}$	N input with atmospheric deposition (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,milk}}$	N output with milk (in kg herd^{-1} lactation^{-1})
$M_{\mathrm{N,\,car}}$	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.

$$\eta_{\mathrm{N}} = \frac{M_{\mathrm{N,\,milk}} + M_{\mathrm{N,\,car}}}{M_{\mathrm{N,\,MF}} + M_{\mathrm{N,\,Leg}} + M_{\mathrm{N,\,AD}}} \qquad (68)$$

where

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

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

where

$E_{\mathrm{X,\,milk}}$	share of a trace gas X attributed to milk production (in kg herd^{-1} lactation^{-1})
$E_{\mathrm{X,\,total}}$	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})
$E_{\mathrm{X,\,meat}}$	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 (≥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 (≥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 (≥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(≥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

$\Delta Y_{\text{milk, dis, n}}$	amount of milk discharged in n-th lactation (in Mg herd^{-1} lactation^{-1})
$Y_{\text{milk, n}}$	milk yield in n-th lactation (in Mg herd^{-1} lactation^{-1})
$I_{\text{sick, n}}$	frequency of illnesses n-th lactation (in cow cow^{-1})
$x_{\text{dis,, n}}$	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:

$$E_{\text{CH4, herd, milk}} = VS_{\text{milk, dis}} \cdot B_{\text{o}} \cdot \rho_{\text{CH4}} \cdot MCF \tag{A4}$$

where

$E_{\text{CH4, herd, milk}}$	CH$_4$ emission from storage caused by discharged milk (in Mg herd^{-1} lactation^{-1} CH$_4$)
$VS_{\text{milk, dis}}$	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

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

where

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

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

where

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

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

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

$$M_{\text{TAN, milk, dis}} = M_{\text{N, milk, dis}} \cdot x_{\text{min, milk}} \tag{A7}$$

$$M_{\text{Norg, milk, dis}} = M_{\text{N, milk, dis}} \cdot \left(1 - x_{\text{min, milk}}\right) \tag{A8}$$

where

$M_{\text{TAN, milk, dis}}$	amount of TAN in discharged milk (in Mg herd^{-1} lactation^{-1})
$M_{\text{N, milk, dis}}$	amount of N in discharged milk (in Mg herd^{-1} lactation^{-1})
$x_{\text{min, milk}}$	fraction of N mineralized in storage N (in kg kg^{-1})
$M_{\text{Norg, milk, dis}}$	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 % DM	handling bad % DM	chosen % 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:

$$m_{\text{j, dis}} = A_{\text{j, sil}} \cdot Y_{\text{j}} \cdot x_{\text{j, dis}} \tag{A9}$$

where

$m_{\text{j, dis}}$	amount of matter lost during removal of an ensiled crop j (in Mg herd^{-1} lactation^{-1})
$A_{\text{j, sil}}$	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})
$x_{\text{j, dis}}$	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.

$$M_{\text{N, dis, j}} = m_{\text{dis, j}} \cdot x_{\text{N, sil, j}} \tag{A10}$$

where

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

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

These are used to quantify N inputs into soils:

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

where

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

$EF_{\text{N2O-N, sm}}$	emission factor for N_2O, solid manure storage (in kg kg^{-1})
$EF_{\text{NO-N, sm}}$	emission factor for NO, solid manure storage (in kg kg^{-1})
$EF_{\text{N2, sm}}$	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 $x_{\text{loss, n}}$ and $x_{\text{loss, n+1}}$. Figure A1 is used to illustrate the calculation procedure to establish a set of animal numbers such as in Tables 2 and 3:

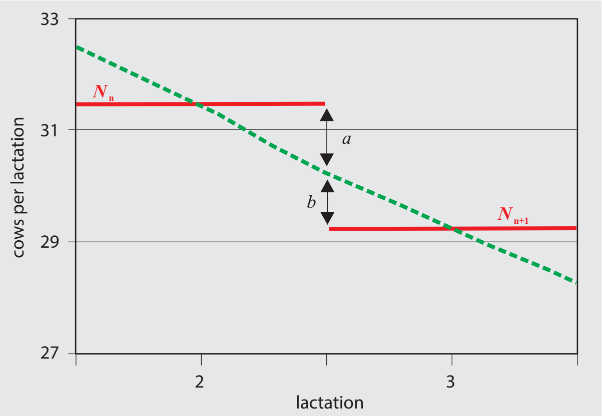

Figure A1
Model describing the number of cows at the beginning and the end of two consecutive lactations

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:

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

and:

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

where

b	difference between number of cows *at the beginning* of lactation n+1, $N_{n+1\text{ B}}$, 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:

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

where

$N_{1,\text{B}}$	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, $N_{2\text{B}}$, 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, $N_{2\text{B}}$, 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.

References

Arbeitsgruppe BZA-Bullenmast (2015) BZA Rind. Land Forst 168(4):30-35

ATT - Arbeitsgemeinschaft Trinkwassertalsperren, BDEW - Bundesverband der Energie- und Wasserwirtschaft, DBVW - Deutscher Bund der verbandlichen Wasserwirtschaft, DVGW - Deutscher Verein des Gas- und Wasserfaches, DWA - Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, VKU - Verband kommunaler Unternehmen (2011) Branchenbild der deutschen Wasserwirtschaft [online]. To be found at <http://www.bdew.de/internet.nsf/id/40873B16E-2024175C125785A00350058/$file/110321_Branchenbild_dt_WaWi_2011_Langfassung_Internetdatei.pdf> [quoted 26.07.2016]

Bastiman B, Altman JFB (1985) Losses at various stages in silage making. Res Develop Agric 2:19-25

Beeker W, Berendonk C, Spiekers H, Rodehutscort M, Tholen E, Pries M (2006) Weide ja oder nein? [online]. To be found at <https://www.landwirtschaftskammer.de/riswick/pdf/forumbeitraege/forum-2006-15-weide.pdf> [quoted 26.07.2016]

Bell MJ, Eckard RJ, Haile-Mariam M, Pryce JE (2013) The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. J Dairy Sci 96:7918–7931

Beyer M, Chudy A, Hoffmann L, Jentsch W, Laube W, Nehring K, Schiemann R (2004) Rostocker Futterbewertungssystem : Kennzahlen des Futterwertes und Futterbedarfs auf der Basis von Nettoenergie. Dummerstorf : Forschungsinst Biol landwirtschaftl Nutztiere, 392 p

BIOGRACE (2012) The BioGrace GHG calculation tool : a recognized voluntary scheme [online]. To be found at <http://biograce.net/content/ghgcalculationtool/recognisedtool> [quoted 26.07.2016]

Brade W, Hamann H, Brade E, Distl O (2008) Untersuchungen zum Verlustgeschehen von Erstkalbinnen in Sachsen. Züchtungskunde 80:127–136

Brentrup F, Pallière CH (2008) Energy efficiency and greenhouse gas emissions in European nitrogen fertilizer production and use. York : Internat Fertiliser Soc, 28 p, Proc Intern Fertilizer Soc 639

Dämmgen U, Haenel H-D, Rösemann C, Hutchings NJ, Brade W, Lebzien P (2009) Improved national calculation procedures to assess energy requirements, nitrogen and VS excretions of dairy cows in the German emission model GAS-EM. Landbauforsch 59(3):233-252

Dämmgen U, Rösemann C, Haenel H-D, Hutchings NJ (2012a) Enteric methane emissions from German dairy cows. Landbauforsch 62(1/2):21-31

Dämmgen U, Amon B, Hutchings NJ, Haenel H-D, Rösemann C (2012b) Data sets to assess methane emissions from untreated cattle and pig slurry and solid manure storage systems in the German and Austrian emission inventories. Landbauforsch 62(1/2):1-20

Dämmgen U, Meyer U, Rösemann C, Haenel H-D, Hutchings NJ (2013) Methane emissions from enteric fermentation as well as nitrogen and volatile solids excretions of German calves : a national approach. Landbauforsch Appl Agric Forestry Res 63(1):37-64

Dämmgen U, Haenel H-D, Rösemann C, Webb J, Brade W, Meyer U (2015b) Modelling excretion rates of German dairy heifers. Landbauforsch Appl Agric Forestry Res 65(2):101-118, DOI:10.3220/LBF1441893614000

Dämmgen U, Brade W, Meyer U, Haenel H-D, Rösemann C, Schwerin M (2015c) Rindfleischerzeugung und Luftverschmutzung : 3. Einfluss einer unterschiedlichen Mastdauer und -intensität auf die Emissionen von Treibhausgasen und Ammoniak bei der Fleischerzeugung mit Fleckvieh-Mutterkuhherden. Züchtungskunde 87:153-180

Dämmgen U, Brade W, Meyer U, Haenel H-D, Rösemann C, Flessa H, Webb J, Strogies M Schwerin M (2016a) Gaseous emissions from protein production with German Holsteins – a mass flow analysis of the entire production chain.: 2. Emissions and reduction potentials. Landbauforsch Appl Agric Forestry Res 66(3):193-214

Dämmgen U, Brade W, Meyer U, Haenel H-D, Rösemann C (2016b) Gasförmige Emissionen (Treibhausgase und Ammoniak) bei der Eiweißerzeugung mit Deutschen Holsteins - eine Stoffstromanalyse der gesamten Produktionskette : 3. Grünlandbasierte Milcherzeugung bei begrenztem Kraftfuttereinsatz. Landbauforsch Appl Agric Forestry Res 66(3):215-228

Dämmgen U, Meyer U, Haenel H-D, Rösemann C, Gruber L, Brade W, Webb J (in preparation) Estimate of emissions of greenhouse gases and air pollutants from German beef production. A revision of methods.

Detterer J, Meinicke-Tillmann S (2011) Four years of practical experience with sexed bull semen in Northwest Germany [online]. To be found at <http://www.aete.eu/index.php/publications-aete/proceedings/84-aete-proceedings-2011/file> [quoted 1.8.2016]

DGE - Deutsche Gesellschaft für Ernährung (2012) The nutrition report 2012 [online]. To be found at <https://www.dge.de/fileadmin/public/doc/en/DGE-Nutrition-Report-summary-2012.pdf> [quoted 26.07.2016]

DLG - Deutsche Landwirtschaftsgesellschaft (1997) DLG-Futterwerttabellen Wiederkäuer. Frankfurt a M : DLG Verl, 212 p

DLG - Deutsche Landwirtschaftsgesellschaft (2014) Bilanzierung der Nährstoffausscheidungen landwirtschaftlicher Nutztiere. Frankfurt a M : DLG Verl, 120 p

DüV (2007) Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen : Fassung vom 27. Februar 2007 [online]. To be found at <http://www.raiffeisen.com/pflanzen/ackermanager/Duengeverordnung.pdf> [quoted 28.07.2016]

EMEP (2013) EMEP-EEA air pollutant emission inventory guidebook - 2013. Technical Report 12/2013 [online]. To be found at <http://www.eea.europa.eu//publications/emep-eea-guidebook-2013> [quoted 28.07.2016]

EU - European Union (2004) Directive 2004/26/EC of the European Parliament and of the Council of 21 April 2004 amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery [online]. To be found at <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004L0026&qid=1469774389082&from=EN> [quoted 28.07.2016]

EU - European Commission (2016) Directive of the European Parliament and the council of on the reduction of national emissions of certain atmospheric pollutants and amending Directive 2003/35/EC, contained in EP-document "PE-CONS No/YY - 2013/0443 (COD)" [online]. To be found at <http://www.emeeting.europarl.europa.eu/committees/agenda/201607/ENVI/ENVI(2016)0711_1/sitt-2813010> [quoted 19.08.2016]

Fischer B (2007) Untersuchungsergebnisse zur Optimierung von Haltung und Fütterung in der Kälberaufzucht : Dummerstorfer Kälber- und Jungrinderseminar am 14.11.2007 [online]. To be found at <http://www.landwirtschaft-mv.de/cms2/LFA_prod/LFA/content/de/Fachinformationen/Tierproduktion/Kaelber-_und_Jungrinderaufzucht/07Kaelber_Jungrinderseminar/Fischer.pdf> [quoted 01.07.2013]

Flachowsky G, Brade W, Feil A, Kamphues J, Meyer U, Zehetmeier M (2011) Carbon (CO$_2$)-Footprints bei der Primärerzeugung von Lebensmitteln tierischer Herkunft : Datenbasis und Reduzierungspotenziale. Übers Tierernähr 39(1):1-45

Fleischer P, Metzner M, Beyerbach M, Hoedemaker M, Klee W (2001) The relationship between milk yield and the incidence of some diseases in dairy cows. J Dairy Sci 84:2025-2035

Flysjö A (2012) Greenhouse gas emissions in milk and dairy product chains : improving the carbon footprint of dairy products. Tjele : Aarhus Univ, 160 p

Frank H, Schmid H, Hülsbergen K-J (2013a) Energie- und Treibhausgasbilanzierung der ökologischen und konventionellen Milchviehhaltung [online]. To be found at <http://www.pilotbetriebe.de/download/Tagung_2013/Frank.pdf> [quoted 27.07.2016]

Frank H, Schmid H, Hülsbergen K-J (2013b) Energie- und Treibhausgasbilanz milchviehhaltender Landwirtschaftsbetriebe in Süd- und Westdeutschland [online]. To be found at <http://www.pilotbetriebe.de/download/Abschlussbericht 2013/5-5_Frank et al 2013.pdf> [quoted 27.07.2016]

Frickh JJ, Baumung R, Luger K, Steinwidder A (2002) Einfluss der Kategorie (Stiere, Ochsen, Kalbinnen) und des Kraftfutterniveaus (Fütterungsintensität) auf der Basis von Gras- und Maissilage auf die Schlachtleistung und Fleischqualität. In: Bericht zur 29. Viehwirtschaftlichen Fachtagung zum Thema Milchproduktion und Rindermast : 24. und 25. April an der BAL Gumpenstein. Irdning : BAL, pp 33-51

Fritsche UR (2003) Energiebilanzen und Treibhausgas-Emissionen für fossile Brennstoffketten und Stromerzeugungsprozesse in Deutschland für die Jahre 2000 und 2020 : Bericht für den Rat für Nachhaltige Entwicklung [online]. To be found at <http://www.nachhaltigkeitsrat.de/uploads/media/Energiebilanzen_fossil_und_Strom_08-03_01.pdf> [quoted 27.07.2016]

Gerber P, Vellinga T, Dietze K, Falcucci A, Gianni G, Mounsey J, Maiorano L, Opio C, Sironi D, Thieme O, Weiler V (2010) Greenhouse gas emissions from the dairy sector : a life cycle assessment [online]. To be found at <http://www.fao.org/docrep/012/k7930e/k7930e00.pdf> [quoted 27.07.2016]

GfE - Gesellschaft für Ernährungsphysiologie (2001) Empfehlungen zur Energie- und Nährstoffversorgung der Milchkühe und Aufzuchtrinder. Frankfurt a M : DLG-Verl, 136 p, Energie- und Nährstoffbedarf landwirtschaftlicher Nutztiere 8

Gordon CH, Derbyshire JC, Wiseman HG, Kane EA, Melin CG (1961) Preservation and feeding value of alfalfa stored as hay, haylage, and direct-cut silage. J Dairy Sci 44:1299-1311

Graf T, Degner J, Zorn W, Pittorf I (2005) Leitlinie zur effizienten und umweltverträglichen Erzeugung von Öllein [online]. To be found at <www.tll.de/ainfo/pdf/oell0805.pdf> [quoted 27.07.2016]

Haenel H-D, Rösemann C, Dämmgen U, Freibauer A, Döring U, Wulf S, Eurich-Menden B, Döhler H, Schreiner C, Osterburg B (2016) Calculations of gaseous and particulate emissions from German agriculture 1990 - 2014 : report on methods and data (RMD) submission 2016. Braunschweig : Johann Heinrich von Thünen-Institut, 409 p, Thünen Rep 39

Harms J (undated, a) Einflussfaktoren wirtschaftlicher Färsenaufzucht [online]. To be found at <www.landwirtschaft-mv.de/cms2/LFA_prod/LFA/content/de/Fachinformationen/Betriebswirtschaft/Oekonomie_Tierproduktion/Faersenaufzucht/Einflussfaktoren_wirtschaftlicher_Frsenaufzucht.pdf> [quoted 27.07.2016]

Harms J (undated, b) Betriebswirtschaftliche Betrachtungen der Lebensleistung und Nutzungsdauer von Milchkühen in Mecklenburg-Vorpommern [online]. To be found at <www.landwirtschaft-mv.de/cms2/LFA_prod/LFA/content/de/Fachinformationen/Betriebswirtschaft/Archiv_Verfahrensoekonomie/_Dateien/Nutzungsdauer_Kuehe.pdf> [quoted 27.07.2016]

Havlik P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC, Mosnier A, Thornton PK, Böttcher H, Conant RT, Frank S, Fritz S, Fuss S, Kraxner F, Notenbaert A (2014) Climate change mitigation through livestock system transitions. Proc Nat Acad Sci USA 111:3709-3711

Heilmann H, Losand B, Jänicke H (2003) Beurteilung der Luzerne als Hochleistungsfutter in der Milchproduktion : Arbeitsbericht. Gülzow : LFA, 23 p

Heinitz F, Albert E, Reinike F, Wagner B (2010) Optimierung N-Management : Analysen des Stickstoff-Managements von Praxisbetrieben in Sachsen auf der Grundlage von Nährstoffbilanzierungen [online]. To be found at <https://www.deutsche-digitale-bibliothek.de/item/KGKN2MYZOJCVJCODSERCR4VUIHNMWDGX> [quoted 27.07.2016]

Hellerich B (2008) Zusammenhänge zwischen Fütterung, Haltung sowie Managementaspekten und der Tiergesundheit in Milchviehbetrieben : (eine statistische Erhebung in Schleswig-Holstein). Hannover : TiHo, 261 p

Hirschfeld J, Weiss J, Preidl M, Korbun Th (2008) Klimawirkungen der Landwirtschaft in Deutschland. Berlin : IÖW, 187 p, SchR IÖW 186

Hogeveen H (2005) Mastitis in dairy production : current knowledge and future solutions. Wageningen : Wageningen Acad Publ, 744 p

Icha P (2014) Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2013 [online]. To be found at <http://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/climate_change_23_2014_komplett.pdf> [quoted 27.07.2016]

IFEU - Institut für Energie- und Umweltforschung (2012) Aktualisierung "Daten- und Rechenmodell: Energieverbrauch und Schadstoffemissionen des motorisierten Verkehrs in Deutschland 1960-2030" (TREMOD, Version 5.3) für die Emissionsberichterstattung 2013 (Berichtsperiode 1990-2011) : Endbericht [online]. To be found at <https://www.ifeu.de/verkehrundumwelt/pdf/IFEU(2012)_Bericht TREMOD FKZ 360 16037_121113.pdf> [quoted 27.07.2016]

IPCC – Intergovernmental Panel on Climate Change (2006a) 2006 IPCC Guidelines for national greenhouse gas inventories : vol 2: Energy [online]. To be found at <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html> [quoted 09.08.2016]

IPCC – Intergovernmental Panel on Climate Change (2006b) 2006 IPCC Guidelines for national greenhouse gas inventories : vol 4: Agriculture, forestry and other land use [online]. To be found at <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html> [quoted 09.08.2016]

IPCC – Intergovernmental Panel on Climate Change (2007) Climate change 2007 : working group I: The physical science basis : 2.10.2: Direct global warming potentials [online]. To be found at <http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html#table-2-14> [quoted 26.07.2016]

Jenssen TK, Kongshaug G (2003) Energy consumption and greenhouse gas emissions in fertiliser production. York : Internat Fertiliser Soc, 28 p, Proc Intern Fertilizer Soc 509

Jiao HP, Dale AJ, Carson AF, Murray S, Gordon AW, Ferris CP (2014) Effect of concentrate feed level on methane emissions from grazing dairy cows. J Dairy Sci 97:1-11

Johnson KA, Kincaid RL, Westberg HH, Gaskins CT, Lamb BK, Cronrath JD (2002) The effect of oilseeds in diets of lactating cows on milk production and methane emissions. J Dairy Sci 85:1509-1515

Kape H-E (2015) Hinweise zur Düngung 2015 [online]. To be found at <http://www.landwirtschaft-mv.de/cms2/LFA_prod/LFA/content/de/Fachinformationen/Acker-_und_Pflanzenbau/AktuellesVeranstaltungen7948/Vortragsmanuskripte/Boden-_und_Duengungstag_2015/9_Kape_Aktuelle_Hinweise.pdf> [quoted 17.08.2016]

Kargo M, Hjortø L, Toivonen M, Erikson JA, Aamand PG, Pedersen J (2014) Economic basis for the Nordic total merit index. J Dairy Sci 97:7879-7888

Kirchgeßner M, Roth FX, Windisch W (1993) Verminderung der Stickstoff und Methanausscheidung von Rind und Schwein durch die Fütterung. Übers Tierernährung 21:89-120

Kirchgeßner M, Roth FX, Schwarz FJ, Stangl G (2008) Tierernährung : Leitfaden für Studium, Beratung und Praxis. Frankfurt a M : DLG Verl, 635 p

Kirchgessner M, Windisch W, Müller HL (1994) Methane release from dairy cows and pigs. In: Aguilera JF (ed) Energy metabolism of farm animals : proceedings of the 13th symposium, Mojacar, Spain, 18-24 September 1994. Granada : CSIC, pp 399-402, EAAP Publ 76

Köhler B, Diepolder M, Ostertag J, Thurner S, Spiekers H (2013a) Dry matter losses of grass, lucerne and maize silages in bunker silos. Agric Food Sci 22:145-150

Köhler B, Diepolder M, Thurner S, Spiekers H (2013b) Effiziente Futterwirtschaft auf Betriebsebene [online]. To be found at <www.lfl.bayern.de/mam/cms07/ite/dateien/effiziente_futterwirtschaft_betriebsebene_30.10.13.pdf> [quoted 27.07.2016]

Krömker V, Pfannenschmidt F (2005) Zur Inzidenz klinischer Mastitiden und ihrer Therapie in Milchviehbetrieben des ökologischen Landbaus. In: Heß J, Rahmann G (eds) Beiträge zur 8. Wissenschaftstagung Ökologischer Landbau „Ende der Nische", Kassel, 1. - 4. März 2005. Kassel : Kassel Univ Pr, pp 409-410

KTBL (2009) Faustzahlen für die Landwirtschaft. Darmstadt : KTBL, 1180 p

KTBL (2010) Gasausbeute in landwirtschaftlichen Biogasanlagen. Darmstadt : KTBL, 36 p, KTBL-Heft 88

KTBL (2014) Betriebsplanung Landwirtschaft 2014/15. Darmstadt : KTBL, 827 p

LfL - Bayerische Landesanstalt für Landwirtschaft (2014) Gruber Tabelle zur Fütterung der Milchkühe, Zuchtrinder, Schafe, Ziegen [online]. To be found at <https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/gruber_tabelle_fuetterung_milchkuehe_zuchtrinder_schafe_ziegen_lfl-information.pdf> [quoted 27.07.2016]

LKW-Nds - Landwirtschaftskammer Niedersachen (2015) Nährstoffbericht in Bezug auf Wirtschaftsdünger für Niedersachsen 2013/2014 [online]. To be found at <https://www.lwk-niedersachsen.de/index.cfm/portal/meldeprogrammwirtschaftsduenger/nav/1787/article/26964.html> [quoted 28.07.2016]

LWK-NRW - Landwirtschaftskammer Nordrhein-Westfalen (2014) Nährstoffbericht NRW 2014 [online]. To be found at <https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/pdf/naehrstoffbericht-nrw-2014.pdf> [quoted 28.07.2016]

LWK-NRW - Landwirtschaftskammer Nordrhein-Westfalen (2015) Stickstoffdüngemittel [online]. To be found at <https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/pdf/n-duengemittel-pdf.pdf> [quoted 28.07.2016]

McGechan MB (1990) A review on losses arising during conservation of grass forage : part 2, storage losses. J Agric Engng Res 45:1-30

Mehl D (2013) Berechnung regionalisierter Stickstoff- und Phosphorbilanzen landwirtschaftlicher Nutzflächen in Mecklenburg-Vorpommern [online]. To be found at <http://service.mvnet.de/_php/download.php?datei_id=104247> [quoted 28.07.2016]

Meyer U, Everinghoff M, Gädeken D, Flachowsky G (2004) Investigations on the water intake of lactating dairy cows. Livest Prod Sci 90:117-121, DOI:10.1016/j.livprodsci.2004.03.005

Meyer U, Stahl W, Flachowsky G (2006) Investigations on the water intake of growing bulls. Livestock Sci 103(1-2):186-191, DOI:10.1016/j.livsci.2006.02.009

Müller-Lindenlauf M, Cornelius Ch, Gärtner S, Reinhardt G, Rettenmaier N, Schmid T (2014) Umweltbilanz von Milch und Milcherzeugnissen : Status quo und Ableitung von Optimierungspotenzialen [online]. To be found at <http://www.milchindustrie.de/uploads/tx_news/IFEU-VDM-Milchbericht-Umweltbilanz-2014_01.pdf> [quoted 26.07.2016]

NIBIS – Niedersächsischer Bildungsserver (2013) Rinderhaltung. Rinderaufzucht, Milchkuhhaltung, Milcherzeugung, Rindermast und Mutterkühe [online]. To be found at <http://www.nibis.de/nibis3/uploads/2bbs-poelking-oesselmann/files/Leitfaden_Rinderhaltung_03.07.2013.pdf> [quoted 01.08.2016

O'Brien D, Capper JL, Garnsworthy PC, Grainger C, Shallow L (2014) A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. J Dairy Sci 97:1835-1851

OECD - Organisation for Economic Co-operation and Development (2001) Environmental indicators for agriculture : methods and results ; executive summary [online]. To be found at <www.oecd.org/greengrowth/sustainable-agriculture/1916629.pdf> [quoted 26.07.2016]

OECD - Organisation for Economic Co-operation and Development (2008) Measuring material flows and resource productivity : synthesis report [online]. To be found at <www.oecd.org/env/indicators-modelling-outlooks/MFA-Synthesis.pdf> [quoted 28.07.2016]

Offermann F, Deblitz C, Golla B, Gömann H, Haenel H-D, Kleinhanß W, Kreins P, Ledebur O von, Osterburg B, Pelikan J, Röder N, Rösemann C, Salamon P, Sanders J, Witte T de (2014) Thünen-Baseline 2013-2023 : agrarökonomische Projektionen für Deutschland. Braunschweig : Johann Heinrich von Thünen-Institut, 112 p, Thünen Rep 19, DOI:10.3220/REP_19_2014

Østergaard S, Gröhn YT (1999) Effects of diseases on test day milk yield and body weight from Danish researchs herds. J Dairy Sci 82:1188-1201

Pahlow G, Meyer U, Greef JM (2003) Mischsilierung von Luzerne mit Silomais. Mitt AG Grünland Futterbau 5:101-104

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. J Dairy Sci 93:1266-1282

Rudolphi B, Harms J, Blum E, Flor J (2012) Verbesserung der Gesundheit, Nutzungsdauer und Lebensleistung von Milchkühen durch Einbeziehung zusätzlicher funktionaler Merkmale in die Selektion [online]. To be found at <http://www.landwirtschaft-mv.de/cms2/LFA_prod/LFA/content/de/Fachinformationen/Tierproduktion/Milcherzeugung/FoBericht_Rudolphi/funktionale_Merkmale_Rudolphi.pdf> [quoted 28.07.2016]

Scholz R, Jeschar R, Jennes R, Fuchs W (1994) Umweltgesichtspunkte bei der Herstellung und Anwendung von Kalkprodukten : Teil 1. Zement-Kalk-Gips 47(10):571-581

Schwerin M (2009) Die Zucht hochleistender und gesunder Kühe - nur ein Traum? Züchtungskunde 81:389-396

Spohr M (2005) Krankheiten und tierärztliche Bestandsergänzung. Landbauforsch Völkenrode SH 289:145-164

StatBA - Statistisches Bundesamt (2014) Düngemittelversorgung : Fachserie 4, Reihe 8.2, Wirtschaftsjahre 2013/2014. Wiesbaden : Statistisches Bundesamt

Steinwidder A (2012) Qualitätsrindermast im Grünland : Mutterkuhhaltung, Jungrinder-, Ochsen-, Kalbinnen-, Bullenmast. Graz : Stocker, 195 pp

Stock KF, Wiebelitz J, Reinhardt F (2014) Health traits and their role for sustainability improvement or dairy production [online]. To be found at <www.gkuh.de/DivDok/VortragEAAP2014_HealthTraitsDairy_S20_18857.pdf> [quoted 28.07.2016]

Südzucker (2014a) Wasser/Abwasser [online]. To be found at <http://www.suedzucker.de/de/FAQ/Zuckergewinnung/Wasser-Abwasser> [quoted 26.07.2016]

Südzucker (2014b) Energie [online]. To be found at <http://www.suedzucker.de/de/FAQ/Zuckergewinnung/Energie> [quoted 26.07.2016]

Thoma G, Popp J, Nutter D, Shonnard D, Ulrich R, Matlock M, Kim DS, Neiderman Z, Kemper N, East C, Adom F (2013) Greenhouse gas emissions from milk production and consumption in the United States : a cradle-to-grave life cycle assessment circa 2008. Int Dairy J 31:S3-S14

Thomet P, Durgiai B (2008) Effizienzparameter der Milchproduktion auf Stufe Betrieb [online]. To be found at <https://www.lfl.bayern.de/mam/cms07/ipz/dateien/aggf_2008_thomet_durgai.pdf> [quoted 26.07.2016]

UBA - Umweltbundesamt, (2015a) Hintergrundbelastungsdaten Stickstoff : Bezugsjahr 2009 [online]. To be found at <gis.uba.de/website/depo1> [quoted 26.07.2016]

UBA - Umweltbundesamt (2015b) Submission 2015 to EMEP5 [online]. To be found at <http://www.ceip.at/ms/ceip_home1/ceip_home/status_reporting/2015_submissions/> [quoted 11.08.2016]

Ullmanns Encyklopädie der technischen Chemie. 19 Bände. München : Urban und Schwarzenberg, 1951 to 1969

van Middelaar CE, Dijkstra J, Berentsen BM, De Boer IJM (2014) Cost-effectiveness of feeding strategies to reduce greenhouse gas emissions from dairy farming. J Dairy Sci 97:2427-2439

van Schooten H, Philipsen B (2012) Grass silage management affecting greenhouse gas emissions and farm economics. In: Kuoppala K (ed) Proceedings of the XVI International Silage Conference, Hämeenlinna, Finland, 2-4 July 2012. Helsinki : MTT Agrifood Research Finland, pp 126-127

van Zijderveld SM, Gerrits WJJ, Dijkstra L, Newbold JR, Hulshof RBA, Perdok HB (2011) Persistency of methane mitigation by dietary nitrate supplementation in dairy cows. J Dairy Sci 94:4028–4038

Vergé XPC, Maxime D, Dyer JA, Desjardins RL, Arcand Y, Vanderzaag A (2013) Carbon footprint of Canadian dairy products : calculations and issues. J Dairy Sci 96:6091-6104

VIT - Vereinigte Informationssysteme Tierhaltung (2014) Trends Fakten Zahlen 2014 [online]. To be found at <www.vit.de/fileadmin/user_upload/wirsindvit/jahresberichte/vit-JB2014-gesamt.pdf> [quoted 26.07.2016]

Weiss J, Pabst W, Strack KE, Granz S (2005) Tierproduktion. Stuttgart : Parey, 579 p

Weissbach F (1993) Grünfutter und Grünfutterkonservate. In: Jeroch H, Flachowsky G, Weissbach F (eds) Futtermittelkunde. Jena : Fischer, pp 74-154

Wilson DJ, González RN, Herti J, Schulte HF, Bennett GJ, Schukken YH, Gröhn TH (2004) Effect of clinical mastitis on the lactation curve : a mixed model estimation using daily milk weights. J Dairy Sci 87:2073-2084

Yan M-J, Humphreys J, Holden NM (2013) The carbon footprint of pasture-based milk production : can white clover make a difference? J Dairy Sci 96:857-865

Zehetmeier M, Baudracco MJ, Hoffmann H, Heissenhuber A (2011) Does increasing milk yield per cow reduce greenhouse gas emissions? : A system approach. Animal 6:154-166

Zoche V, Spilke J (2012) Die Kosten der Eutergesundheit - Milchverluste [online]. To be found at <https://www.landwirtschaft.sachsen.de/landwirtschaft/download/BWFG_Milch_Zoche_13_09_2012.pdf> [quoted 26.07.2016]