Enteric methane emissions from German dairy cows

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Abstract

Up to now, the German agricultural emission inventory used a model for the assessment of methane emissions from enteric fermentation that combined an estimate of the energy and feed requirements as a function of performance parameters and diet composition, with the constant methane conversion rate provided in the IPCC guidelines. The two existing guidelines propose two different constant rates (IPCC, 1996: 6.0 % or 60 kJ MJ^{-1}, and IPCC, 2006: 6.5 % or 65 kJ MJ^{-1}, of the gross energy intake, respectively). Both constants do not reflect that the rates should be dependent on feed properties, as stated by IPCC. A methane emission model was selected here that is based on German feed data. It was combined with the hitherto applied model describing energy requirements.

The emission rates thus calculated deviate from those previously obtained. In the new model, the methane conversion rate is back-calculated from emission rates and gross energy intake rates. For German conditions of animal performance and diet composition, the national means of methane conversion rates range between 71 kJ MJ^{-1} and 61 kJ MJ^{-1} for low and high performances (4700 kg $animal^{-1}$ a^{-1} in 1990 to 7200 kg $animal^{-1}$ a^{-1} in 2010), respectively.

Keywords: methane, emission, model, enteric fermentation, dairy cows

Zusammenfassung

Methan-Emissionen aus der Verdauung bei deutschen Milchkühen

Im Emissionsinventar für die deutsche Landwirtschaft erfolgte die Berechnung der Methan-Emissionen aus der Verdauung bei Milchkühen bisher mit Hilfe eines Modells, das Energie- und Futterbedarf anhand von Leistungsparametern und Futtereigenschaften beschreibt, und einer in den IPCC-Richtlinien vorgegebenen Methan-Umwandlungsrate. Die beiden zur Verfügung stehenden Richtlinien schlagen zwei unterschiedliche (konstante) Raten vor (IPCC, 1996: 6,0 % bzw. 60 kJ MJ^{-1}, und IPCC, 2006, 6,5 % bzw. 65 kJ MJ^{-1} von eingesetzter Bruttoenergie), die allerdings nicht die von IPCC ebenfalls erwähnte Abhängigkeit von den Futtereigenschaften aufweisen. Daher wurde ein geeignetes, auf nationalen Futterdaten beruhendes Methan-Emissionsmodell identifiziert und mit dem bisher im Inventar verwendeten Energiebedarfsmodell kombiniert.

Die so berechneten Emissionsraten weichen von den bisher erhaltenen ab. Im neuen Emissionsmodell wird die zu berichtende Methan-Umwandlungsrate aus Emissionen und Bruttoenergie-Aufnahme zurückgerechnet. Für das deutsche Spektrum an Leistung und Fütterung ergeben sich im nationalen Mittel Umwandlungsraten zwischen 71 kJ MJ^{-1}bei geringen Leistungen und 61 kJ MJ^{-1} bei hohen Leistungen (4700 kg $animal^{-1}$ a^{-1} in 1990 bis 7200 kg $animal^{-1}$ a^{-1} in 2010).

Schlüsselwörter: Methan, Emission, Modell, Verdauung, Milchkühe

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1 Introduction

Emissions of methane (CH_4) from domestic animals contribute to global warming and to regional air pollution (e.g. Möller, 2011). Any measures to reduce the adverse effects presuppose a satisfactory description of the processes leading to emissions and the adequate assessment of these emissions. In 2009, about 50 Gg a^{-1} CO_2-eq were calculated to have been emitted as CH_4 in Germany, more than half of which originate from agriculture. Within agriculture, the most prominent source category is enteric fermentation of dairy cows, contributing more than 50 % of the overall agricultural CH_4 emissions (Freibauer et al., 2011). At present, the assessment of these emissions makes use of a detailed calculation of energy requirements, but uses the default IPCC methane conversion rate (MCR) of 60 kJ MJ^{-1} of the gross energy (GE) intake (IPCC, 1996) instead of the IPCC (2006) default MCR of 65 kJ MJ^{-1}. These default values do not take feed properties into account. However, animal performance has changed over the two decades covered by emission reporting to UNFCCC. Increased animal weights, increased milk yields and changes in milk protein and fat contents have required different diets. The share of grain in diets has increased since 1990. Hence the MCR should have decreased.

The aim of this work is to establish national emission factors and methane conversion rates for CH_4 from enteric fermentation of dairy cows as a function of animal performance and diet composition.

2 Formation of methane in the rumen and its description in models

In the rumen of cattle, the organic matter in feed is subject to microbial degradation that forms volatile fatty acids (VFA), gases (carbon dioxide, CO_2, and CH_4) and microbial biomass and releases adenosine triphosphate (ATP) as source of energy. The CH_4 formation rate is dependent on diet composition. Lowest emissions per unit of dry matter (DM) intake originate from cereal rich diets, highest from diets rich in fibre and with a low digestibility. For a detailed description of these processes see e.g. Jouany (2008).

Numerous models have been published that allow the prediction of CH_4 emissions from dairy cows as a function of performance and diet composition (for reviews see Jouany, 2008, or Ellis et al., 2007). The quality of the resulting predictions is to a large extent dependent on the number of input parameters available. A very detailed model (Dijkstra et al., 1992; modified by Mills et al., 2001) makes use of the input rates of neutral detergent fibre (NDF: cellulose, hemicellulose, lignin), protein, ammonia, water soluble carbohydrates, starch, lipids, lactate and VFA. Such a model predicts emissions that can be in good agreement with experimental data (Benchaar et al., 1998) or can contradict them (Hinrichs et al., 2004). However, the required (very) detailed data on diet composition is not routinely collected in Germany.

German data sets obtained in respiration chambers are available. Linear regression models based on these measurements were published in Kirchgeßner et al. (1994a) as well as in Jentsch et al. (2007) and Piatkowski et al. (2010). The equations provided in Jentsch et al. (2007) and used in Piatkowski et al. (2010) differ, even though they were derived from the same experimental data set. In these three publications, a number of equations for emissions factors are provided. In the following, those with the highest coefficient of correlation are selected (in chronological order).

2.1 Detailed regression model of Kirchgeßner et al. (1994a)

Kirchgeßner et al. (1994a) reported on their experiments with lactating dairy cows and their approach to relate CH_4 emissions to the crude nutrient intake.

Model 2 in Kirchgeßner et al. (1994a) relates emission factors to the following parameters for lactating dairy cows:

$$EF_{CH4,1} = a_1 \cdot M_{XFi} + b_1 \cdot M_{NFE} + c_1 \cdot M_{XP} + d_1 \cdot M_{XF} + e_1 \quad (1)$$

where

$EF_{CH4,1}$ methane emission rate (factor) (in kg $animal^{-1}$ a^{-1}) according to Kirchgeßner et al. (1994a)
a_1 coefficient (a_1 = 0.079 kg kg^{-1})
M_{XFi} intake rate of crude fibre (in kg $animal^{-1}$ a^{-1})
b_1 coefficient (b_1 = 0.010 kg kg^{-1})
M_{NFE} intake rate of N-free extracts (in kg $animal^{-1}$ a^{-1})
c_1 coefficient (c_1 = 0.026 kg kg^{-1})
M_{XP} intake rate of crude protein (in kg $animal^{-1}$ a^{-1})
d_1 coefficient (d_1 = – 0.212 kg kg^{-1})
M_{XFa} intake rate of ether extract (fat) (in kg $animal^{-1}$ a^{-1})
e_1 constant (e_1 = 365 · 0.063 kg $animal^{-1}$ a^{-1})

Kirchgeßner et al. (1995) applied the same equation successfully to other cattle. They provide a comparison between observed and predicted emissions (Figure 1).

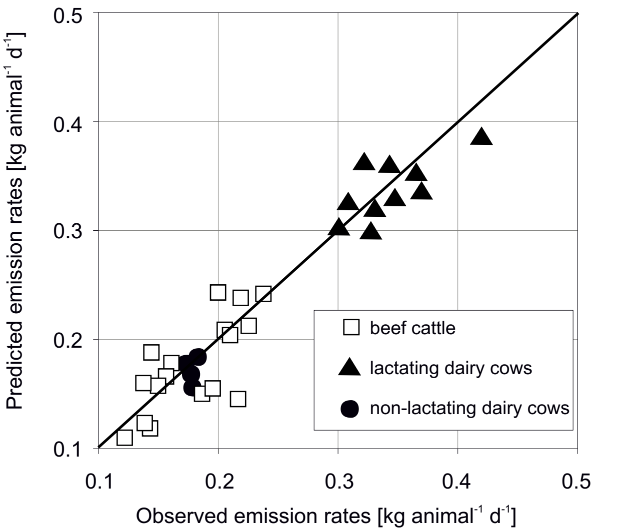

Figure 1:

Comparison of observed and predicted emission rates, as published in Kirchgeßner et al. (1995), based on additional data from Beyer et al. (1993) and Kirchgeßner et al. (1980, 1994b) (redrawn). Slope: 0.99; R^2 = 0.92)

2.2 *Simple regression model approach of Kirchgeßner et al. (1994a)*

Kirchgeßner et al. (1994a) also interpreted the experimental data set using dry matter as sole explaining entity (see Equation (2) below). This is equivalent to the IPCC methodology in principle as the GE content of dry matter, η_{GE}, is almost constant (IPCC default η_{GE} = 18.45 MJ kg^{-1}, see also Dämmgen et al., 2011). The following equation resulted:

$$EF_{CH4,2} = a_2 \cdot m_{DM} + b_2 \tag{2}$$

where

$EF_{CH4,2}$ CH_4 emission rate (in g animal^{-1} d^{-1})
a_2 coefficient (a_2 = 12 g kg^{-1})
m_{DM} dry matter intake rate (in kg animal^{-1} a^{-1})
b_2 constant (b_2 = 134 g animal^{-1} a^{-1})

with a coefficient of regression of R^2 = 0.19.

The IPCC methodology describes a direct relation without an intercept (constant b_2 = 0).

2.3 *Detailed regression model of Jentsch et al. (2007)*

Respiration experiments with oxen, young bulls, heifers, lactating and non-lactating dairy cows of Black Pied cattle covering a wide range of body weights yielded a number of regression equations relating CH_4 formation with diet properties. Of these, the following relation offered the best description (Equation 6 in Jentsch et al., 2007, transformed):

$$EF_{CH4,3} = \frac{1}{\eta_{CH4}} \cdot \left(a_3 \cdot m_{DP} + b_3 \cdot m_{DF} + c_3 \cdot m_{DST} + d_3 \cdot m_{DSU} + e_3 \cdot m_{DNFR} + f_3\right) \tag{3}$$

where

$EF_{CH4,3}$ CH_4 emission rate (in kg animal^{-1} a^{-1}) according to Jentsch et al. (2007)
η_{CH4} energy content of methane (η_{CH4} = 55.65 MJ (kg CH_4)$^{-1}$)
a_3 coefficient (a_3 = 1.28 MJ kg^{-1})
m_{DP} intake rate of digestible crude protein (in kg animal^{-1} a^{-1})
b_3 coefficient (b_3 = -0.31 MJ kg^{-1})
m_{DF} intake rate of digestible crude fat (in kg animal^{-1} a^{-1})
c_3 coefficient (c_3 = 1.31 MJ kg^{-1})
m_{DST} intake rate of digestible starch (in kg animal^{-1} a^{-1})
d_3 coefficient (d_3 = 1.16 MJ^{-1})
m_{DSU} intake rate of digestible sugar (in kg animal^{-1} a^{-1})
e_3 coefficient (e_3 = 2.40 MJ kg^{-1})
m_{DNFR} digestible N-free extracts (in kg animal^{-1} a^{-1})
f_3 constant (f_3 = 1.835 MJ animal^{-1} d^{-1} · 365 d a^{-1})

The coefficient of regression was R^2 = 0.889.

2.4 *Simple regression model of Jentsch et al. (2007) as used by Piatkowski et al. (2010)*

Piatkowski et al. (2010) used the simple approach developed by Jentsch et al. (2007) (Equation (4)) requiring just two variables, the DM intake and the live weight of the animals:

$$EF_{CH4,4}{}^{*} = a_4 \cdot \frac{m_{DM}}{w} + b_4 \tag{4}$$

where

$EF_{CH4,4}{}^{*}$ specific CH_4 emission related to feed intake (in g (kg DM)$^{-1}$ d^{-1} CH_4)
a_4 coefficient (a_4 = 0.384 kg kg^{-1})
m_{DM} dry matter intake rate (in g d^{-1})
w live weight (in kg)
b_4 constant (b_4 = 32.76 g (kg DM)$^{-1}$ d^{-1} CH_4)

The coefficient of regression was R^2 = 0.224.

2.5 Selecting the adequate model

2.5.1 Input data

All regression models proposed by Kirchgeßner et al. (1994) and by Jentsch et al. (2007) were derived from different German data sets reflecting different animal performances and feed constituents.

The models described in Kirchgeßner et al. (1994a) were originally based on 153 records from respiration trials using lactating cows with milk yields from 10 to 30 kg animal^{-1} d^{-1} and weights between 450 and 700 kg animal^{-1}. The performance data used within the emission inventory are well covered by these data. The results were described and discussed in great detail in the paper and in preceding publications (in particular Kirchgeßner et al., 1991).

The models established by Jentsch et al. (2007) are based on a re-evaluation of experimental data obtained between 1957 and 1989 in 337 experiments with Black Pied cattle, including 42 dairy cows. The live weights of the cows varied between 420 and 672 kg animal^{-1} with a mean of 547 kg animal^{-1}. Milk yields are not reported. A graph is provided showing the methane emissions in energy equivalents as a function of DM intake related to body weight.

2.5.2 Comparing the models using a national set of animal performance, feed intake, diet composition and properties of diet constituents

In order to assess the results obtained with the equations (1) to (4) listed above independent of energy requirement calculations, a standard data set published as an example for nutrient excretion modelling in DLG (2005) was applied to them. The only animal performance entity varied is ECM (energy corrected milk yield). The amounts of the different diet constituents proposed are shown in Table 1, the relevant feed properties in Table 2.

The relevant properties of the diet constituents grass silage, maize silage, hay, straw, soya bean extraction meal and wheat were extracted from Beyer et al. (2004). Standard concentrates (MLF) contents of water, crude ash, crude protein, crude fat, starch and sugar and organic matter were obtained from measurements performed at Riswick experimental station (LWK-NRW, 2004 to 2011). All in all, 132 analyses were taken into consideration.

The calculation of the concentration of nitrogen free extracts (NfE) is a standard operation in the Weender feed analysis (see e.g. Kirchgeßner et al., 2008). It is obtained as residue as follows:

$$x_{\mathrm{NfE}} = x_{\mathrm{OM}} - \left(x_{\mathrm{XP}} + x_{\mathrm{XFa}} + x_{\mathrm{XFi}}\right) \quad (5)$$

where

x_{NfE} concentration of nitrogen free extracts in a feed constituent (in kg kg^{-1})
x_{OM} organic matter content in a feed constituent (in kg kg^{-1})
x_{XP} crude protein content in a feed constituent (in kg kg^{-1})
x_{XFa} crude fat content in a feed constituent (in kg kg^{-1})
x_{XFi} crude fibre content in a feed constituent (in kg kg^{-1})

Table 1:
Composition of diets proposed for dairy cows in DLG (2005). Amounts in kg animal^{-1} a^{-1}.

feed variant *	G1	G2	G3	A1	A2	A3	GH1	GH2	GH3	AH1	AH2	AH3
milk yield (ECM)	6000	8000	10000	6000	8000	10000	6000	8000	10000	6000	8000	10000
grass	1900	1600	1300	1000	1000	1000	0	0	0	800	800	800
grass silage	1900	2200	2500	1100	1300	1500	3300	3300	3250	900	1100	1300
maize silage	400	700	1000	2000	2200	2400	400	700	1000	2000	2200	2400
hay	0	0	0	0	0	0	500	500	500	500	500	500
straw	200	200	200	300	200	200	200	200	200	200	100	100
soya bean extraction meal	0	100	250	200	300	450	0	100	250	200	300	450
wheat	200	200	250	100	200	250	200	200	250	100	200	2050
standard concentrate**	1300	1700	2200	1200	1500	1900	1400	1800	2300	1200	1500	1900
mineral feed	10	15	20	20	25	30	10	15	20	20	25	30
total	5910	6715	7720	5920	6725	7730	6010	6815	7770	5920	6725	7730

* feed variants: G: grassland farms, no hay fed; A: mixed farms, predominantly arable land, no hay fed; GH: grassland farms, hay fed; AH: mixed farms, predominantly arable land, hay fed
** standard concentrate MLF 18/3[1], in variant G1 MLF 16/3. For our calculations MLF 16/3 was replaced by MLF 18/3

[1] MLF: Milchleistungsfutter, concentrate for dairy cows

Table 2:
Properties of relevant diet constituents (for sources see text)

contents related to DM	gross energy	digestible crude protein	digestible crude fat	digestible starch	digestible sugars	digestible N free residues	crude fibre	N-free extracts	crude protein	crude fat
	η_{GE}	η_{DP}	η_{DF}	η_{DST}	η_{DSU}	η_{DNFR}	η_{Fi}	η_{NFE}	η_{XP}	η_{XF}
unit	MJ kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}
feed constituent										
grass silage	18.5	0.112	0.024	0.029	0.049	0.426	0.245	0.452	0.162	0.042
maize silage	17.9	0.038	0.020	0.146	0.061	0.406	0.228	0.582	0.080	0.028
hay	18.0	0.066	0.014	0.029	0.058	0.439	0.280	0.485	0.115	0.025
straw	18.1	0.008	0.007	0.010	0.010	0.402	0.450	0.425	0.038	0.017
rape seed extraction meal	23.6	0.311	0.060	0.046	0.078	0.212	0.130	0.350	0.370	0.070
soya bean extraction meal	20.0	0.446	0.010	0.048	0.092	0.239	0.080	0.345	0.495	0.015
wheat	18.5	0.110	0.014	0.631	0.032	0.072	0.030	0.785	0.145	0.020
standard concentrate *	18.7	0.169	0.029	0.212	0.083	0.095	0.115	0.554	0.216	0.042
mineral feed	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

* standard concentrate MLF 18/3

Inverting Equation 10.21 in IPCC (2006) yields the definition of the MCR which is obtained from the GE intake rate and the amount of CH_4 emitted:

$$MCR = \frac{EE_{CH4}}{GE} = \eta_{CH4} \cdot \frac{EF_{CH4}}{GE} \qquad (6)$$

where

MCR methane conversion rate (in MJ MJ^{-1})
EE_{CH4} energy equivalent of methane excreted (in MJ animal^{-1} a^{-1})
GE gross energy intake rate (in MJ animal^{-1} a^{-1})
η_{CH4} energy content of CH_4 (η_{CH4} = 55.65 MJ kg^{-1})
EF_{CH4} methane emission factor (in kg animal^{-1} a^{-1} CH_4)

As a consequence, the MCR can be considered a measure of energy loss by CH_4 emission from enteric fermentation.

The results obtained from the application of Equations (1) to (4) are collated in Figure 2.

As shown in Figure 2, all MCR values decrease with increasing GE intake rates. The values obtained with Equation (3) are highest and exceed the results obtained with both IPCC approaches. The application of Equation (4) yields results above the IPCC (2006) value for GE intake rates below 120 GJ animal^{-1} a^{-1}, and values in the same range as the IPCC (2006) default value for a GE intake rates above 120 GJ animal^{-1} a^{-1}. The estimates using the procedures published by Kirchgeßner et al. (1995) fall below the IPCC (2006) estimates and below the IPCC (1996) in many cases.

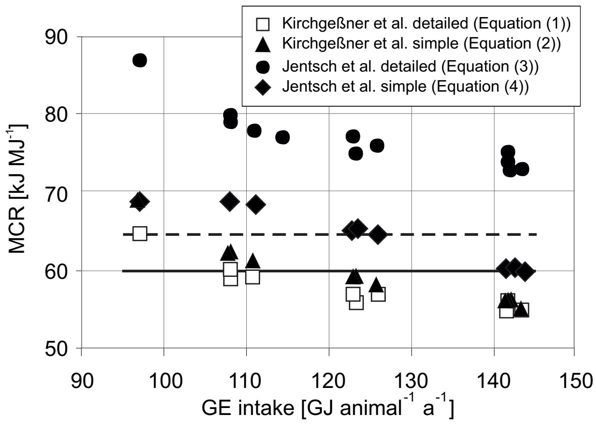

Figure 2.

Methane conversion rates predicted by the models of Kirchgeßner et al. (1994a) (Equations (1) and (2)) and Jentsch et al. (2007) (Equations (3) and (4)) as well as the IPCC (1996) (solid line) and IPCC (2006) dotted line) default values as a function of the gross energy intake.

None of the models agree with the results predicted by the IPCC (1996) and (2006) default values. This may be due to the method to assess the energy requirements and/or the method assessing the CH_4 emission rates.

Hence, the structures of the models calculating these entities have to be investigated and comparisons reported in the literature have to be used as an instrument for selection of the methodology to be applied in the German emission inventory.

2.5.3 The adequate model

Both simple regression models (Equations (2) and (4)) do not provide a mechanistic tool to reflect feed properties as key variables governing *MCR* appropriately. Piatkowski et al. (2010) claim this to be necessary. Hence it is not unexpected that both simple models yield rather low coefficients of regression when compared to the other two models (Equations (1) und (3)). As a consequence, both simple models cannot be considered adequate models.[2]

In an intercomparison using a New Zealand data set, the more detailed model by Kirchgeßner et al. (1994a) [3] (Equation (1)) was found to predict emissions falling below measured data (Palliser and Woodward, 2002).

Bannink et al. (2011) modelled rumen chemistry and published results of CH_4 emissions from Dutch dairy cattle derived from feed properties only. The values for the back-calculated *MCR* are very close to the IPCC (1996) default *MCR*. However, no comparison with measured data is provided. Nevertheless it underpins the likelihood that *MCR* close to 60 kJ MJ^{-1} reflect the reality for cows with a milk yield of about 7000 kg $animal^{-1}$ a^{-1}.

Equation (1) was included in a comparison of observed and predicted emissions together with the IPCC (1996) Tier 2 methodology in Ellis et al. (2010). In comparison with the so-called individual data base (of emissions) both approaches yielded modelled data that exceeded the observed data by about 8 % (Ellis et al., 2010, Table 3). The evaluation states that "Kirchgeßner et al. [1995, Eq. 1] performed better than most other equations on the TRT [4] database". For whole farm models, the equation is clearly more appropriate than the other models in the comparison, in particular IPCC (1996) Tier 2 (see Ellis et al., 2010, Figure 2).

Other than the more detailed model by Kirchgeßner et al. (1994a) [5] (Equation (1)) the recently published results by Jentsch et al. (2007) (Equation 3) were not yet involved in international model intercomparisons.

For the following reasons we conclude that the model defined by Equation (1) represents the best choice out of the four models available:

- it was derived from experimental data covering German dairy cow husbandry which are well documented,
- it is based on mechanistic considerations,
- it requires input data that are available for all German diet constituents,
- it is the only German model which has performed satisfactorily in international comparisons.

3 Combining the module predicting energy requirements and the detailed Kirchgeßner et al. (1994a) module

The German agricultural emission inventory model GAS-EM uses a module to assess energy requirements and dry matter intake for dairy cows based on experimental data obtained in Austria, Germany and Switzerland. The approach is derived from GfE (2001) and DLG (2006) and is described in detail in Dämmgen et al. (2009). Recent changes are documented in Haenel et al. (2012). The establishment of the data base can be found in Dämmgen et al. (2010). This module was combined with the procedure proposed in the Tier 2 methodologies in IPCC (1996) and (2006) to calculate CH_4 emissions from enteric fermentation.

3.1 The IPCC methodology

Both the IPCC (1996) and (2006) guidelines provide the same Tier 2 methodology to assess CH_4 emissions from dairy cows. The major steps are

- the identification of the performance data
- the assessment of the net energy requirements
- the derivation of GE intake rates
- the application of an *MCR* to quantify CH_4 emission rates.

The data flow within this module is shown in Figure 3.

IPCC (2006), Table 10.12, provides default values for *MCR* of 65 (± 10) kJ MJ^{-1} of the GE intake rate. However, Johnson and Johnson (1995) illustrate that observed *MCR* can vary between 20 and 110 kJ MJ^{-1}, also that the *MCR* modelled according to Blaxter and Clapperton (1965) exceeds 60 kJ MJ^{-1} in any case. This is also true for the *MCR* measured by Lassey (2007) – the other source cited in IPCC (2006). However, it remains unclear whether the data sets can reflect the situation of lactating cows in Germany, as diet composition and performance differ.

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[2] It is confusing that IPCC (2006) refer to Johnson and Johnson (1995) as a source for *MCR* whose evaluation of a data set relating GE intake and the *MCR*.results with a coefficient of correlation of 0.05.

[3] Kirchgeßner et al. (1995) quote Kirchgeßner et al. (1994a) as origin of the equation used.

[4] " … a literature derived treatment average database (37 data points from seven studies)…." (Ellis et al., 2010)

[5] see footnote 3

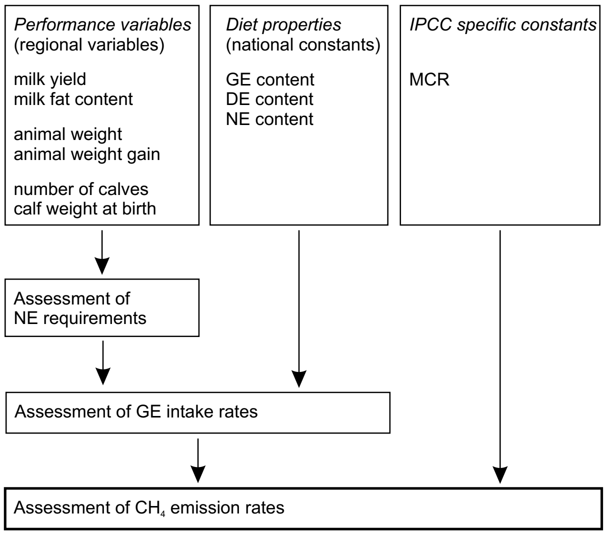

Figure 3:

Flow of data within the IPCC module to assess methane emissions from dairy cows

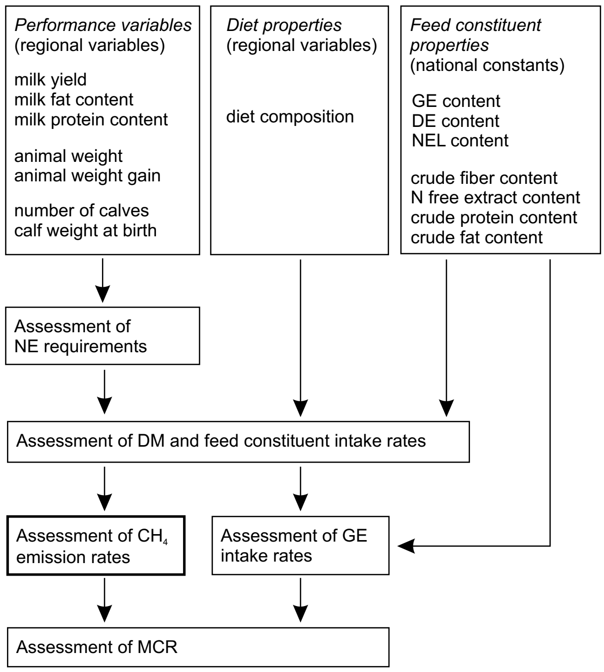

Figure 4:

Flow of data within the combined modules to assess methane emissions from dairy cows

3.2 The combination of the energy and feed intake and the Kirchgeßner modules

The module describing energy requirements and feed intake rates in GAS-EM makes use of the NEL [6] requirements to assess the feed intake as a function of milk yield, milk protein and fat contents, body weight and weight gain, the development of conception products as well as the grazing time to cover the requirements to obtain feed and the energy contents of roughage and concentrates.

For each German district, a grass based diet (constituents: pasture grass, grass silage, wheat, MLF, ratios depending on performance) and a mixed diet typical for farms with arable land (constituents: pasture grass, grass silage, maize silage, rape seed expeller, MLF, ratios depending on performance) are considered. The shares of the two types vary between districts and between years, as does the duration of grazing and hence the share of pasture grass in the diets.

This module is combined with the Kirchgeßner module as defined by Equation (1) to derive CH_4 emission rates. The data flow is illustrated in Figure 4. Note that the role of MCR differs in the IPCC and the combined approach used here, as the latter calculate MCR as a diagnostic entity. The calculation procedure needs the GE intake rate as an auxiliary entity.

4 Sensitivity analysis of the combined modules

The combined energy, feed intake and the Kirchgeßner modules as described above yield CH_4 emission rates. International reporting of CH_4 emissions from enteric fermentation delivers MCR as an entity to characterize the emission process. Hence, our sensitivity analysis concentrates on this entity. It was performed changing one input parameter at a time, *ceteris paribus*. The range of variation of those parameters reflects those of the potential input data.

A dimensionless sensitivity indicator S is defined by

$$S = \frac{\frac{\Delta MCR}{MCR_{st}}}{\frac{\Delta P}{P_{st}}} \qquad (7)$$

where

S	sensitivity indicator (dimensionless)
ΔMCR	variation of MCR (in kJ MJ^{-1})
MCR_{st}	MCR at standard conditions (in kJ MJ^{-1})
ΔP	variation of the input parameter P
P_{st}	value of the input parameter P at standard conditions

6 NEL: net energy for lactation

Table 4:
Entities varied in the sensitivity analysis

	feed type	range	range	standard value	variation	unit
Entitiy varied		from (min)	to (max)	P_{st}	ΔP	
milk yield	mixed	4600	8100	6000	600	kg animal^{-1} a^{-1}
milk yield	grass	4600	8100	6000	600	kg animal^{-1} a^{-1}
milk fat	mixed	0.040	0.043	0.041	0.0041	kg kg^{-1}
milk fat	grass	0.040	0.043	0.041	0.0041	kg kg^{-1}
milk protein	mixed	0.033	0.036	0.034	0.0034	kg kg^{-1}
milk protein	grass	0.033	0.036	0.034	0.0034	kg kg^{-1}
live weight	mixed	580	670	620	62	kg animal^{-1}
live weight	grass	580	670	620	62	kg animal-1
weight gain	mixed	10	20	13.3	1,33	kg animal^{-1} a^{-1}
grazing time	grass	0.00	0.39	0	1	h d^{-1}

Table 5:
Sensitivity of *MCR* towards varied input parameters (*MCR* in kJ MJ^{-1})

	feed type	*MCR*	*MCR*	MCR_{st}	S_1	S_{graz}
Entity varied		from	to		%	%
milk yield	mixed	73.4	62.2	68.1	-0.30	
milk yield	grass	69.4	60.4	65.5	-0.24	
milk fat	mixed	68.4	67.6	68.1	-0.15	
milk fat	grass	65.7	65.2	65.5	-0.11	
milk protein	mixed	68.3	67.8	68.1	-0.07	
milk protein	grass	65.6	65.3	65.5	-0.05	
live weight	mixed	68.8	67.8	68.1	-0.10	
live weight	grass	66.1	65.3	65.5	-0.09	
weight gain	mixed	68.2	68.0	68.1	-0.04	
grazing time	grass	65.5	64.2	65.5		-0.1

The sensitivity indicator S_1 used reflects changes in *MCR* (in %) as result of a variation of *P* of 1 %. For grazing, the indicator S_{graz} shows the effect of 1 h additional grazing per day.

A negative *S* indicates that an increase in *P* results in a decrease in *MCR*.

For a given performance, diets richer in grass or grass silage result in reduced *MCR*.

Extended grazing also leads to reduced *MCR*.

It should be kept in mind that decreasing *MCR* do not necessarily result in decreased CH_4 emission rates, but that increased performance will result in increased CH_4 emission rates per animal.

5 Application of the combined modules to German dairy cows

5.1 Case study reflecting regional peculiarities

Dairy cows representing three different regions and performance classes were selected for an example calculation. Their respective properties are collated in Table 6.

Variants 6M and 6G were selected representing cows in Bayern (Bavaria) with 6000 kg animal^{-1} a^{-1}. They differ with respect to their feeding: M denotes mixed feeding (diet contains pasture grass, grass silage, maize silage, rape seed expeller, MLF, ratios depending on performance), G refers

Table 6:

Animal performance data and grazing regimes used in the example calculations (for symbols see text)

Variant	6M	6G	7Mv	7Gv	7Mc	7Gc	8Mv	8Gv	8Mc	8Gc	
milk yield	6000	6000	7200	7200	7200	7200	8400	8400	8400	8400	kg animal^{-1} a^{-1}
final weight	675	675	650	650	675	675	620	620	675	675	kg animal^{-1}
initial weight	650	650	620	620	650	650	580	580	650	650	kg animal-1
lifespan	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	a
milk fat content	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	kg kg^{-1}
milk protein content	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	kg kg^{-1}
share on mixed feed	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	animal animal^{-1}

Table 7:

Methane emission rates and methane conversion rates obtained in the example calculations (for symbols see text)

Variant	6M	6G	7Mv	7Gv	7Mc	7Gc	8Mv	8Gv	8Mc	8Gc	
CH_4 emission rate	130.0	125.6	133.3	128.8	134.5	130.0	136.3	131.9	139.0	134.3	kg animal^{-1} a^{-1}
MCR	67.5	65.1	64.2	62.4	64.0	62.2	61.4	59.9	59.9	59.6	kJ MJ^{-1}

to a grass based diet (pasture grass, grass silage, wheat, MLF, ratios depending on performance). Dairy cows with a milk yield of 7200 kg animal^{-1} a^{-1} (7M and 7G) are likely to be found in Niedersachsen (Lower Saxony). These animals are lighter than those in Bavaria. In order to eliminate potential effects of different live weights, one additional variant keeps weights and weight gains constant (7Mc and 7Gc), whereas 7Mv and 7Gv use the varied weights. The same applies to the high performance cows 8M and 8G with a milk yield of 8400 kg animal^{-1} a^{-1} which may be located in present Mecklenburg-Vorpommern.

Grazing time was kept constant for all variants, i.e. the share of animals housed permanently was 85 %, that of animals grazing part time 15 %. The latter were grazed 12 hours per day and 170 days per year.

The resulting CH_4 emission rates and *MCR* are listed in Table 7.

Table 7 illustrates the ranges of CH_4 emission rates and *MCR* to be considered, indicating that *MCR* will fall below the IPCC (1996) default value of 60 kJ MJ^{-1} on a national scale if milk yields continue to increase. It also shows that the low milk yields as in the early 1990s will result in *MCR* well above the IPCC (2006) default value of 65 kJ MJ^{-1}.

5.2 Application to the time series of German dairy cow performance and grazing data used in the national inventory

In order to illustrate the effect of the application of the combined modules to the German national inventory, a data set containing national weighted means of all parameters described above (milk yield, milk fat and protein contents, weight, weight gain, diet composition and feed properties as well as grazing times) was used to establish a time series of national *MCR* (Figure 5).

MCR decrease almost steadily primarily as a result of increasing milk yields (4700 kg animal^{-1} a^{-1} in 1990 to 7200 kg animal^{-1} a^{-1} in 2010). Projections expect mean milk yields of 7800 kg animal^{-1} a^{-1} in 2020, which are likely to result in *MCR* of about 61 kJ MJ^{-1}. Again, animals kept on mixed farms emit more CH_4 per MJ GE than those receiving a grass based diet.

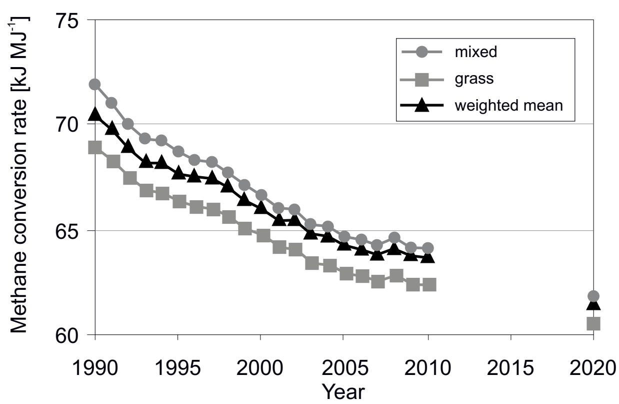

Figure 5:

Time series of mean methane conversion rates obtained from German inventory data

6 Discussion

CH_4 emission rates from enteric fermentation depend on performance data such as weight and weight gain, milk yield, concentrations of milk fat and protein. They are also governed by feed properties and the rumen microflora.

The IPCC approach (IPCC, 1996; IPCC, 2006) describes CH_4 emission rates from enteric fermentation as proportional to the GE intake rates (divided by the energy content of CH_4) where the constant of proportionality is the so called methane conversion rate MCR. The gross energy can be calculated as function of the energy requirements which in turn are a function of the animal performance. The only feed property considered is the digestibility of energy.

It is striking that – given the importance of CH_4 emissions from enteric fermentation – the experimental data base is sparse.

The data sets that are the base of the IPCC's MCR fixing suffer from this inadequacy. The data used in Johnson and Johnson (1995) obviously originate from North American measurements. They illustrate however that the approach to derive CH_4 emission rates from GE intake rates may be inadequate. In addition, they state that an approach that takes feed properties into account (such as in Moe and Tyrrell, 1979) yields better results and should be preferred. The data set provided by Lassey (2007), based on tracer techniques, illustrates the variability of MCR but does not allow for a direct comparison. The five French cows used in the measurements were obviously dry and of a heavy breed.

The investigations made for the present paper clearly indicate that the use of a constant MCR is inadequate. Any approach to derive MCR has to reflect at least feed composition and feed properties. It should also reflect a typical rumen microflora (see Dijkstra and France, 1996; Ellis et al., 2008; Hook et al., 2010). Both aspects require national solutions, i.e. national feed property data and national data on diet composition as a function of animal performance data (American and European conditions differ substantially with respect to diet composition data, see Table 2 in Mills et al., 2003). Assuming a "mean national microflora", the emissions from the various feed constituents have to be obtained from experiments. Germany is fortunate in having both data sets at hand. In the combined GAS-EM and Kirchgeßner modules they can be used as parameters to derive energy requirements, CH_4 emissions and non-constant MCR.

Even if the experimental results used in this work are now two decades old and have not been checked or updated since, they are not contradiced by more modern data (such as those reported in Lassey, 2007, Hindrichsen et al., 2004, Jouany, 2008, and Ellis et al., 2009).

Hence, it is recommended that the updated GAS-EM module reflecting diet composition and feed properties leading to variable methane conversion rates for dairy cows according to Kirchgeßner et al. (1994a) be applied in future German agricultural emission inventories.

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