Enteric methane emissions from German pigs

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Abstract

Methane emissions from enteric fermentation of pigs are object of emission reporting. Hitherto they were treated as part of the energy balance of pigs, in accordance with IPCC guidance documents. They were calculated from the gross energy intake rate and a constant methane conversion ratio. Meanwhile numerous experimental data on methane emissions from enteric fermentation is available in Germany and abroad; the results are compiled in this work. These results also allow for a description of transformation processes in the hind gut and a subsequent establishment of models that relate emissions to feed and performance data.

The model by Kirchgeßner et al. (1995) is based on German experimental data and reflects typical national diet compositions. It is used to quantify typical emissions and methane conversion ratios. The results agree with other experimental findings at home and abroad.

The application of the model results in emission rates that fall below those calculated with the IPCC standard procedures by about one fifth.

Keywords: methane, emission, model, enteric fermentation, pigs

Zusammenfassung

Methan-Emissionen aus der Verdauung bei deutschen Schweinen

Die Methan-Emissionen aus der Verdauung bei Schweinen sind Gegenstand der Emissionsberichterstattung. Sie wurden bisher nach Vorgaben des IPCC-Regelwerks als Bestandteil der Energiebilanzen von Schweinen aus der Gesamtenergie-Aufnahmerate und einem (festen) Methan-Umwandlungsfaktor berechnet. Mittlerweile liegen zahlreiche experimentelle Untersuchungen aus dem In- und Ausland zu Methan-Emissionen aus der Verdauung vor, deren Ergebnisse in diesem Beitrag zusammengefasst sind. Aus den Ergebnissen dieser Messungen lassen sich in Kenntnis der Umsetzungsprozesse im Enddarm Modelle ableiten, die eine Quantifizierung der Emissionen aus Fütterungs- und Leistungsdaten erlauben.

Das aus deutschen Daten abgeleitete Modell von Kirchgeßner et al. (1995) dient dazu, aus den aus Umfragen erhaltenen Futterzusammensetzungen in Deutschland typische Emissionen und Methan-Umwandlungsraten berechnen. Die mit dem Modell erhaltenen Ergebnisse stimmen mit anderen experimentellen Befunden aus dem In- und Ausland überein.

Im Mittel werden danach Emissionsraten errechnet, die um ein Fünftel unter den nach dem derzeit gültigen IPCC-Standardverfahren berechneten liegen.

Schlüsselwörter: Methan, Emission, Modell, Verdauung, Schweine

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Introduction

Methane (CH_4) is a greenhouse gas and air pollutant. International conventions require that its emissions be quantified and reported. [1] In animal production, CH_4 emissions originate from enteric fermentation and from manure storage. In Central Europe these emissions are dominated by the emissions from enteric fermentation of cattle. Emissions from enteric fermentation of pigs are of minor importance albeit not negligible (German data for 2010: estimated emissions from enteric fermentation in pig production 26.3 Gg a^{-1} CH_4, total CH_4 emissions from agriculture 1,231 Gg a^{-1} CH_4; Haenel et al., 2012).

At present, emission reporting makes use of the IPCC (1996) guidance document that relates CH_4 emissions from enteric fermentation to the gross energy (GE) intake using a default methane conversion rate (MCR) of 0.6 % (expressed as energy loss; IPCC, 1996, Table A-4). It is unclear whether this tool is adequate for the environmental valuation of changes in feeding practices, as GE may differ with feed composition – feed intake is governed by metabolizable energy (ME). In contrast to IPCC (1996), IPCC (2006), Table 10.12, entirely omits pigs as sources of methane from enteric fermentation.

This work develops a national approach to quantify emissions from enteric fermentation in pig production for the purpose of emission reporting, using experimental data and modelled data based on German national diet compositions. It concludes the series of publications that revised the treatment of emissions from pig production in the national agricultural emission inventory. [2]

1 Experimental data – an overview

1.1 Measurement technique

CH_4 emissions can be measured using respiratory chambers (see eg Kirchgeßner et al., 2008, pg 151f) where animals are kept for a few hours up to a few days. Care is taken that faeces are removed before they can contribute to relevant emissions. Gas exchange in these chambers is recorded continuously. However, during their stay in the chamber the animals lack social contact. Furthermore, their physical activity is restricted. Normally, the release of CH_4 is related to standing up (Jørgensen et al., 2011), so the intestinal activity pigs within a respiration chamber may be abnormal. However, there is experimental evidence that the overall energy balance is not changed significantly (Gray and McCracken, 1980), so it is also likely that the CH_4 emission rates are not greatly affected by the lack of physical activity.

1.2 Measured methane emission rates

Several European groups measured CH_4 emission rates from non-lactating sows and growing pigs. In most cases the measurements were part of feeding experiments, including variations of the share of fibre fed. In these cases, emission rates for the respective control group only are considered in the following Tables 1 to 3. In the literature, emission rates are presented as mass, volume or energy contents of CH_4 emitted per animal per day. If performance data are mentioned in the publications, an attempt is made to relate emissions to the GE intake rate. The following relations are used for conversion:

Conversion of digestible energy

$$GE = \frac{DE}{X_{DE}} \tag{1}$$

where

GE gross energy intake rate (in MJ $animal^{-1}$ d^{-1})
DE digestible energy intake rate (in MJ $animal^{-1}$ d^{-1})
X_{DE} digestibility of energy (default X_{DE} = 0.866 MJ MJ^{-1}; Müller and Kirchgeßner, 1983a)

Conversion of metabolizable energy

$$GE = \frac{ME}{X_{ME}} \tag{2}$$

where

GE gross energy intake rate (in MJ $animal^{-1}$ d^{-1})
ME metabolizable energy intake rate (in MJ $animal^{-1}$ d^{-1})
X_{ME} metabolizability of energy (as a rule provided in the literature) (in MJ MJ^{-1})

Conversion of net energy

$$GE = \frac{NE}{X_{NE}} \tag{3}$$

where

GE gross energy intake rate (in MJ $animal^{-1}$ d^{-1})
NE net energy intake rate (in MJ $animal^{-1}$ d^{-1})

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[1] For air pollutants, reporting was required within the Geneva Convention on Long-Range Transboundary Air Pollution until 2002. Since then reporting has been mandatory within the United Nations Framework Convention on Climate Change only.

[2] Redistribution of animal numbers (Haenel et al., 2011a), update of energy requirements (Haenel et al., 2011b), feed composition (Dämmgen et al., 2011a), volatile solids excretion (Dämmgen et al., 2011b, nitrogen excretion (Dämmgen et al., 2010), methane emission from storage (Dämmgen et al., 2012), basic ammonia emission factors and amounts of bedding (Eurich-Menden et al., 2011).

X_{NE} ratio of net to gross energy (default X_{NE} = 0.53 MJ MJ^{-1})

Conversion of volume to mass

The density ρ_{CH4} of CH_4 is 0.716 kg m^{-3} at standard conditions. (German standard DIN 1343 uses a standard temperature $T_{n, DIN}$ = 273.15 K and a standard pressure of 1013 hPa. Gas densities (ρ) can then be adjusted using the relation $T_{n,1}/T_{n,2} = \rho_2/\rho_1$.)

Conversion of mass to energy

The energy content η_{CH4} of CH_4 is 55.65 MJ kg^{-1}.

Units frequently used to describe CH_4 emission rates and relate them to animal or feed properties

- EV_{CH4} denotes the volume of CH_4 emitted per animal and per unit of time.
- EV_{CH4}^* (specific volume) relates the volume of CH_4 emitted to the metabolic weight of the animal.
- EM_{CH4} is the mass of CH_4 emitted per animal and per unit of time.
- EE_{CH4} is the energy equivalent of the CH_4 released per animal and per unit of time.
- EE_{CH4}^* is the specific energy equivalent of the CH_4 released per unit of metabolic animal weight and per unit of time.

The methane conversion ratio MCR is the fraction of gross energy taken in that is converted to CH_4 in the hind gut. [3]

$$MCR = \frac{EE_{CH4}}{GE} \quad (4)$$

where

MCR methane conversion ratio (in kJ MJ^{-1})
EE_{CH4} energy equivalent of methane released (in kJ animal^{-1} d^{-1})
GE gross energy intake rate (in MJ animal^{-1} d^{-1})

Table 1:
Methane emissions from sows (for the symbols used see explanations above)

reported entity	reported value	unit	live weight (LW) kg animal^{-1}	notes	MCR kJ MJ^{-1}	reference
MCR	0.7	% GE		early gestation	7	Beyer et al. (1994)
MCR	0.4	% GE		late gestation	4	Beyer et al. (1994)
MCR_{DE}	0.7	% DE	205	lactating	5.3	Jakobsen et al. (2005)
MCR_{DE}	1.31	% DE	225		10.1	Jørgensen (2007)
MCR_{DE}	0.8	% DE			6.7	Jørgensen et al. (2001)
MCR_{DE}	0.7	% DE	210		5.5	Jørgensen et al. (2007)
MCR	0.74	% GE	203		7.4	Kirchgeßner and Müller (1981)
MCR	0.94	% GE	187		9.4	Kirchgeßner et al. (1987)
MCR_{DE}	0.88	% DE	235		6.6	le Goff et al. (2002b)
EE_{CH4}	0.3	MJ d^{-1}	190		9.2	Müller and Kirchgeßner (1983a)
MCR_{DE}	0.6	% DE	201	increased straw	5.2	Müller and Kirchgeßner (1983b)
EE_{CH4}	0.25	MJ animal^{-1} d^{-1}			7.6	Müller and Kirchgeßner (1985a)
MCR_{DE}	0.8	% DE	184		6.9	Müller and Kirchgeßner (1985b)
MCR_{DE}	0.8	% DE	239		6.9	Noblet and Le Goff (2001)
SE [A]	0.21	MJ (kg DM)$^{-1}$	208		11.4	Noblet et al. (1993)
MCR_{DE}	1.2	% DE	290		9.8	Olesen et al. (2001)
MCR_{DE}	0.85	% DE	260	low fibre	7.4	Ramonet et al. (2000)
MCR_{DE}	3.36	% DE	260	high fibre	29	Ramonet et al. (2000)
MCR_{DE}	0.8	% DE	183	high protein	6.7	Theil et al. (2002)
MCR_{DE}	0.5	% DE	175	low protein	4.2	Theil et al. (2002)
MCR_{DE}	0.73	% DE	206		6.4	Theil et al. (2004), Jørgensen et al. (2011)

[A] SE: specific emission (see unit)

[3] The IPCC terminology uses the symbol Y_m (IPCC: methane conversion factor) (in MJ MJ^{-1}) for the methane conversion ratio MCR (used in this work). IPCC also call the ratio with which CH_4 is formed within manure storage a methane conversion factor (in %) and apply the symbol MCF.

In some cases, the methane conversion ratio is not related to gross energy. Instead, MCR_{DE}, is used to describe the fraction of digestible energy taken in that is converted to CH_4 in the hind gut.

$$MCR_{DE} = \frac{EE_{CH4}}{DE} \quad (5)$$

where

MCR_{DE} methane conversion ratio for digestible energy (in kJ MJ^{-1})
EE_{CH4} energy equivalent of methane released (in kJ $animal^{-1}$ d^{-1})
DE digestible energy intake rate (in MJ $animal^{-1}$ d^{-1})

The live weight LW (in kg $animal^{-1}$) is used to characterize the animals.

1.2.1 Sows

Measurements on sows were published almost only for non-lactating animals (Table 1). It is customary to feed sows in this time span a diet that is high in fibre. Hence, the emissions listed in Table 1 cannot be extrapolated to annual emission rates.

1.2.2 Piglets

As sows milk does not contain fibre or polysaccharides, suckling piglets should not produce CH_4. However, milk replacer does contain fibre which results in small CH_4 emission rates (Table 2).

Table 2:
Methane emissions from piglets fed on milk replacer (for the symbols used see explanations above)

reported entity	reported value	unit	live weight (LW) kg $animal^{-1}$	MCR kJ MJ^{-1}	reference
EV_{CH4}	0.13	l $animal^{-1}$ d^{-1}	4.9	1.2	Theil et al. (2007), Jørgensen et al. (2011)

1.2.3 Growing pigs

Growing pigs comprise both weaners and finishing pigs. However, the measurements available only deal with finishing pigs. As a rule, animal weights and weight gains are reported (Table 3).

1.3 Résumé

The data collated originate from measurements in Germany, Denmark, The Netherlands, France, Italy as well as from The USA, Canada and China. Care was taken that the results obtained for the control groups were extracted from the articles. In some cases it was difficult to identify the control.

The number of animals in the respective experiments varied from "a few" to "many". Hence the calculation of *weighted* mean values of MCR was impossible. However, the calculation of *arithmetic* mean values may be used to support results obtained from modelling.

For **sows**, only 1 result describes lactating animals (Jacobsen et al., 2005). The 30 values obtained for gestating sows can be reduced to a arithmetic mean MCR of about 7.0 kJ MJ^{-1}. If one keeps in mind that diets for gestating sows are richer in fibre than those for lactating sows, and that the energy intake with feeds during the lactation phase is about one third of the overall GE intake (Haenel et al., 2011b), then a weighted mean MCR of less than 7.0 kJ MJ^{-1} results.

$$MCR_{sow,\,mean} = \frac{2 \cdot MCR_{sow,\,gest} + 1 \cdot MCR_{sow,\,lact}}{3} \quad (6)$$

Data listed in Table 1 suggest an MCR of about 6.5 kJ MJ^{-1}.

Only one reference could be found for **suckling piglets**. The MCR of 1.2 kJ MJ^{-1} can be ignored considering the low GE intake of these animals and the small share of milk replacer fed in addition to sows' milk.

The majority of data sets describe **growing pigs**. 3 papers refer to animals in the subcategory of weaners (LW < 35 kg $animal^{-1}$) for which an MCR of about 3 kJ MJ^{-1} can be identified. For finishing pigs, a mean MCR of about 4.5 kJ MJ^{-1} can be calculated; here, the results published by Atakora et al. (2011) are considered outliers and omitted from this and subsequent calculations.

Experiments with varying animal weights (*ceteris paribus*) showed that MCR increases with animal weight (e.g. Christensen and Thorbek, 1987; Noblet and Shi, 1994). A regression analysis leads to the same conclusion, although the scatter is considerable (Figure 1).

MCR also increases with the fibre content of the diet (e.g. Jensen and Jørgensen, 1994) and with increasing protein content (e.g. Theil et al., 2002).

The IPCC (1996) default MCR exceeds almost all values derived from measurements.

Table 3:
Methane emissions from growing pigs

reported entity	reported value	unit	live weight (LW) kg animal^{-1}	notes	MCR kJ MJ^{-1}	reference
EM_{CH4}	17.0	g animal^{-1} d^{-1}	81	very low protein, barley	25.3	Atakora et al. (2011)
EM_{CH4}	17.6	g animal^{-1} d^{-1}	81	medium protein, barley	27.3	Atakora et al. (2011)
EM_{CH4}	23.2	g animal^{-1} d^{-1}	75	high protein, barley	36.3	Atakora et al. (2011)
EM_{CH4}	23.9	g animal^{-1} d^{-1}	63	medium protein, maize	39.4	Atakora et al. (2011)
EM_{CH4}	25.4	g animal^{-1} d^{-1}	63	high protein, barley	42.1	Atakora et al. (2011)
MCR_{DE}	0.4	% DE	80		3.5	Barea et al. (2010)
EV_{CH4}	1.7 to 8.5	l animal^{-1} d^{-1}	20 to 25	feed varied	5.4	Christensen and Thorbek (1987)
EV_{CH4}	12.2 to 8.5	l animal^{-1} d^{-1}	35 to 110	feed varied	5.2 to 11.0	Christensen and Thorbek (1987)
MCR	0.45	% GE	85		4.5	Galassi et al. (2004)
EV_{CH4}	1.4	l animal^{-1} d^{-1}	112 to 132	low fibre	0.8	Jensen and Jørgensen (1994)
EV_{CH4}	12.5	l animal^{-1} d^{-1}	112 to 132	high fibre	7.1	Jensen and Jørgensen (1994)
MCR	0.4 to 0.5	% GE	30 to 125		4 to 5	Jentsch and Hofmann (1977)
MCR	0.05	% GE	13 to 28		0.5	Jentsch et al. (1991)
MCR	0.44	% GE	28 to 63		4.4	Jentsch et al. (1991)
EM_{CH4}	1.13	g animal^{-1} d^{-1}	60		2.8	Ji et al. (2011)
EM_{CH4}	2.01	g animal^{-1} d^{-1}	90		3.4	Ji et al. (2011)
MCR_{DE}	0.49	% DE	65		4.2	Jørgensen (2007)
MCR_{DE}	0.2	% DE	20	low fibre	1.9	Jørgensen et al. (1996a)
MCR_{DE}	1.1	% DE	20	high fibre	9.0	Jørgensen et al. (1996a)
MCR_{DE}	0.51	% DE	20		4.0	Jørgensen et al. (1996b)
MCR_{DE}	0.8	% DE	60 to 115		6.7	Jørgensen et al. (2007)
MCR_{DE}	0.4	% DE	35		3.1	Jørgensen et al. (2001)
MCR_{DE}	0.80	% DE	60 to 115		6.7	Jørgensen et al. (2007)
MCR_{DE}	0.70	% DE	65.2		6.1	Le Bellego et al. (2001)
MCR_{DE}	0,46	% DE	65.9		4.1	Le Bellego et al. (2001)
MCR_{DE}	0,60	% DE	65.5		5.3	Le Bellego et al. (2001)
MCR_{DE}	0,50	% DE	65.2		4.3	Le Bellego et al. (2001)
MCR_{DE}	0.20	% DE	41		1.8	le Goff et al. (2002a)
MCR_{DE}	0.24	% DE	76		2.2	le Goff et al. (2002a)
MCR_{DE}	0.41	% DE	43		3.5	Noblet and Shi (1994)
MCR_{DE}	0.44	% DE	48		3.8	Noblet and Shi (1994)
MCR_{DE}	0.60	% DE	100		5.2	Noblet and Shi (1994)
EE_{CH4}	0.14	MJ animal^{-1} d^{-1}	75 to 90		4.3	Schneider and Menke (1982)
EV_{CH4}*	0.242	l kg - 0.75 d^{-1}	48		8.5	Schrama et al. (1996)
EE_{CH4}*	4.9	kJ kg - 0.75 d^{-1}	54		3.9	Schrama et al. (1998)
EE_{CH4}*	6.2	kJ kg - 0.75 d^{-1}	46		4.8	Schrama et al. (2003)
MCR_{DE}	0.29	% DE	33 to 60		2.8	Wang et al. (2004)

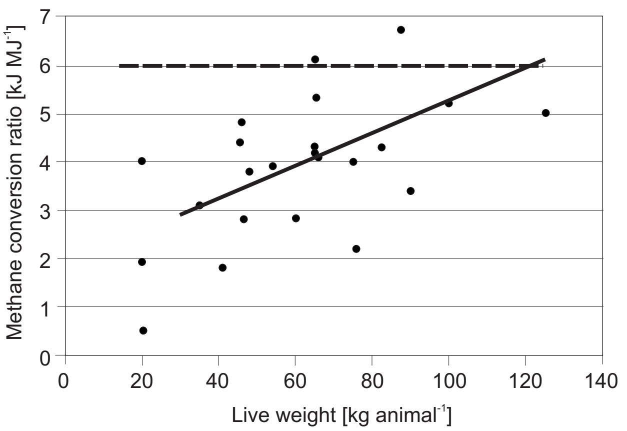

Figure 1:

Methane conversion ratios of growing pigs as a function of live weight using those data sets from Table 3 where weights and *MCR* were provided. Full line: regression for pigs with 30 kg animal^{-1} ≤ LW ≤ 125 kg animal^{-1}; R^2 = 0.34. Dotted line: default *MCR* in IPCC (1996)

2 Modelling methane formation in pigs

Modelling should allow for the weighing of effects and side effects of potential reduction measures, in particular the influence of diet composition and feeding practices on emissions. However, this requires a more mechanistic approach relating emissions to animal performance and feed constituents than provided in IPCC (1996).

2.1 Methane formation in the digestive system

The formation of CH_4 in the digestive system (enteric fermentation) of pigs is mainly centred in the hind gut (colon) (see Jensen and Jørgensen, 1994). Here, bacterial action degrades those organic species that passed the digestive tract undigested, mainly cellulose, hemicellulose and pectin which are summed up as bacterially fermentable substrates (BFS). Bacterial action converts these substrates to volatile fatty acids, CH_4 and carbon dioxide (see Figure 2). The fatty acids play an important role in the energy supply of pigs (Kirchgeßner et al., 1987; Dierick et al., 1989; Noblet and Le Goff, 2001). In experiments with sows, about half the cellulose and about 90 % of the sugar (xylose), starch [4] and cellulose (pectin) as well as the protein casein that were applied to the animals intracaecally were degraded in the hind gut (Kreuzer et al., 1991a, b). Despite the efforts described e.g. in Kirchgeßner et al. (1987, 1991) or Noblet (2007), Jørgensen et al. (2011) state "However, information on how dietary composition and intrinsic animal factors influence gas production in pigs is rather limited."

2.2 Relating methane emission rates to feed intake, diet composition and animal performance

A number of relationships have been developed to predict enteric CH_4 emission to dietary or animal characteristics. In this section, we briefly review these relationships. Note that Equations 8 to 11 return the CH_4 emission per feeding day. To calculate the annual emission per place, the so-called emission factor EF_{CH4}, it is necessary to take account of the duration of any period during which the place is empty (e.g. for cleaning).

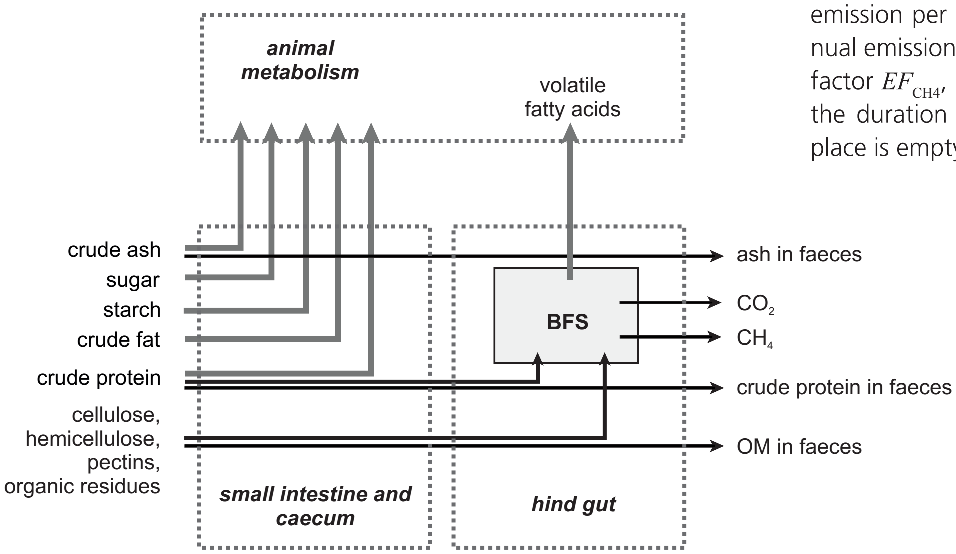

Figure 2:

Pathways of major feed constituents through the gut of pigs. Gray arrows: share of constituents that can be resorbed. Wide black arrows: bacterially fermentable substrates; narrow black arrows: matter that is neither resorbable nor bacterially fermentable.

[4] Sugars and starch will normally be digested in the small intestine and caecum (see Figure 2).

The relation between emission factor (emission per place per year) and emission rate (emission per animal per day) is as follows:

$$EF_{CH4} = E_{CH4} \cdot t_{lifespan} \cdot n_{round} \quad (7)$$

where

EF_{CH4} CH_4 emission factor (in kg place^{-1} a^{-1} CH_4)
E_{CH4} CH_4 emission rate (in kg animal^{-1} d^{-1} CH_4)
$t_{lifespan}$ duration of lifespan in a subcategory (in d)
n_{round} number of animal rounds (in animal place^{-1} a^{-1})

2.2.1 Model 1: methane formation rate and BFS supply rate

From respiration chamber measurements Kirchgeßner et al. (1991) deduced functions describing emission rates for growing pigs and for sows.

$$E_{CH4,1} = a_1 + b_1 \cdot m_{BFS} = a_1 + b_1 \cdot DM \cdot \eta_{BFS} \quad (8)$$

where

$E_{CH4,1}$ CH_4 emission rate obtained with model 1 (in kg animal^{-1} d^{-1} CH_4)
a_1 constant (in kg animal^{-1} d^{-1})
b_1 coefficient (in kg kg^{-1} CH_4)
m_{BFS} rate of BFS available for fermentation (in kg animal^{-1} d^{-1})
DM dry matter intake rate (in kg animal^{-1} d^{-1})
η_{BFS} mean BFS content of feed (dry matter) (in kg kg^{-1})

Both constant and coefficient vary between growing pigs and sows, for sows also with the mean BFS content η_{FBS}. Kirchgeßner et al. (1991) propose to differentiate between three cases:

growing pigs:
in any case a_1 = 0.00000 kg animal^{-1} d^{-1}; b_1 = 0.020 kg kg^{-1}

sows:
if η_{BFS} < 0.08 kg kg^{-1} then a_1 = 0.00000 kg animal^{-1} d^{-1}; b_1 = 0.020 kg kg^{-1}
if η_{BFS} ≥ 0.08 kg kg^{-1} then a_1 = 0.00285 kg animal^{-1} d^{-1}; b_1 = 0.013 kg kg^{-1}

Boars (mature males for reproduction) are treated like sows.

The comparatively low regression coefficients R^2 of about 0.6 can be explained by variations in the individual digestion processes, including variations in the composition of the bacterial populations.

2.2.2 Models 2 and 3: methane formation rate and supply rate of fermented dietary fibre (FDF)

Model 2 is defined by an equation deduced by Noblet et al. (2004) (as quoted in Noblet, 2007):

$$E_{CH4,2} = a_2 \cdot \frac{m_{FDF}}{\eta_{CH4}} \quad (9)$$

where

$E_{CH4,2}$ CH_4 emission rate obtained with model 2 (in kg animal^{-1} d^{-1} CH_4)
a_2 coefficient (growing pigs: a_2 = 0.67 MJ (kg FDF)$^{-1}$; sows: a_2 = 1.33 MJ (kg FDF)$^{-1}$)
m_{FDF} supply rate of fermented dietary fibre (FDF) (in kg animal^{-1} d^{-1})
η_{CH4} energy content of CH_4 (η_{CH4} = 55.65 MJ kg^{-1})

A similar approach was published in Jørgensen (2011). It is used as model 3:

$$E_{CH4,3}{}^* = a_3 + b_3 \cdot m_{FDF} \quad (10)$$

where

$E_{CH4,3}{}^*$ CH_4 emission rate obtained with model 3 (in l animal^{-1} d^{-1} CH_4)
a_3 constant (growing pigs: a_3 = 0.440 l animal^{-1} d^{-1} CH_4; sows: a_3 = 0.626 l animal^{-1} d^{-1} CH_4)
b_3 coefficient (growing pigs: b_3 = 0.0206 l (kg FDF)$^{-1}$; sows: b_3 = 0.00894 l (kg FDF)$^{-1}$)
m_{FDF} supply rate of fermented dietary fibre (FDF) (in kg animal^{-1} d^{-1})

2.2.3 Model 4: methane formation rate, feed intake and animal weight

If the diet composition is kept constant, CH_4 emissions vary with dry matter (DM) intake. This again is related to animal weight or metabolic weight. An equation is provided in Jørgensen (2011, Equation 3):

$$E_{CH4,4}{}^* = a_4 + b_4 \cdot w \quad (11)$$

where

$E_{CH4,4}{}^*$ CH_4 emission rate obtained with model 4 (in l animal^{-1} d^{-1} CH_4)
a_4 constant (a_4 = 1.01 l animal^{-1} d^{-1} CH_4)
b_4 coefficient (b_4 = 0.0107 l (kg LW)$^{-1}$ d^{-1})
w live weight of the animal (in kg animal^{-1})

2.2.4 IPCC (1996) approach: methane conversion ratio and gross energy intake

If feed composition is about constant, then fibre and feed intake rates are proportional to the gross energy (GE) intake rate of the animals. This simplification is used by IPCC (1996) without any further differentiation of animal subcategories to deduce the emission per place and year. The constant is called the methane conversion ratio (MCR) in the IPCC nomenclature.

$$EF_{\mathrm{CH4,\,IPCC}} = \frac{MCR \cdot GE}{\eta_{\mathrm{CH4}}} \quad (12)$$

where

$EF_{\mathrm{CH4,\,IPCC}}$	CH_4 emission factor obtained with the IPCC (1996) approach (in kg place^{-1} a^{-1} CH_4)
MCR	coefficient (MCR = 6 kJ MJ^{-1})
GE	gross energy intake (in MJ place^{-1} a^{-1})
η_{CH4}	energy content of CH_4 (η_{CH4} = 55.65 MJ kg^{-1})

3 The recommended methodology: application of the Kirchgeßner approach to the German dataset of feed intake rates and diet composition

Based on the brief review above, we conclude that since the formation of CH_4 in the hind gut is mechanistically related to the availability of BFS and that any approach that relates emissions to this entity should be preferred over others. In Germany, the fraction of bacterially fermentable substrates in diet constituents is a standard entity listed among feed properties. Furthermore, low but nevertheless satisfactory correlations were established experimentally in Germany (see Kirchgeßner et al., 1991, and literature cited therein). Keeping in mind that the conversion of undigested carbohydrates in the hind gut also depends on the state of health of the animal and the microbial population in the gut, we nevertheless consider that the most promising method should relate the formation of methane to the undigested fibre available.

3.1 The methodology

The methodology is based on the equation reported by Kirchgeßner et al. (1991) which relates the rate of CH_4 emissions to the rate of BFS supplied to the hind gut (see Equation 7).

The rate of BFS supplied in the diet is calculated from the diet composition using Equation (13) (see Kirchgeßner et al., 2008, pg 169).

$$\begin{aligned} m_{\mathrm{BFS,\,i}} &= \\ &\eta_{\mathrm{BFS,\,i}} \cdot m_{\mathrm{DM,\,i}} = \\ &m_{\mathrm{OM,\,i}} \cdot x_{\mathrm{D,\,OM,\,i}} - m_{\mathrm{XP,\,i}} \cdot x_{\mathrm{D,\,XP,\,i}} - \\ &m_{\mathrm{XF,\,i}} \cdot x_{\mathrm{D,\,XF,\,i}} - \left(m_{\mathrm{st,\,i}} + m_{\mathrm{su,\,i}}\right) \end{aligned} \quad (13)$$

where

$m_{\mathrm{BFS,\,i}}$	rate of BFS available for fermentation in a feed constituent i (in kg animal^{-1} d^{-1})
$\eta_{\mathrm{BFS,\,i}}$	BFS content of a feed constituent i (in kg kg^{-1})
$m_{\mathrm{DM,\,i}}$	intake rate of dry matter with a feed constituent i (in kg animal^{-1} d^{-1})
$m_{\mathrm{OM,\,i}}$	intake rate of organic matter with a feed constituent i (in kg animal^{-1} d^{-1})
$x_{\mathrm{D,\,OM,\,i}}$	digestibility of organic matter in feed constituent i (in kg kg^{-1})
$m_{\mathrm{XP,\,i}}$	intake rate of crude protein with a feed constituent i (in kg animal^{-1} d^{-1})
$x_{\mathrm{D,\,XP,\,i}}$	digestibility of crude protein in feed constituent i (in kg kg^{-1})
$m_{\mathrm{XF,\,i}}$	intake rate of crude fat with a feed constituent i (in kg animal^{-1} d^{-1})
$x_{\mathrm{D,\,XF,\,i}}$	digestibility of crude fat in feed constituent i (in kg kg^{-1})
$m_{\mathrm{st,\,i}}$	intake rate of starch with a feed constituent i (in kg animal^{-1} d^{-1})
$m_{\mathrm{su,\,i}}$	intake rate of sugars with a feed constituent i (in kg animal^{-1} d^{-1})

BFS contents of single feed constituents $\eta_{\mathrm{BFS,\,i}}$ are obtained from a modified Weender analysis (cf Kirchgeßner et al, 2008, pg 22 f) and are produced as a matter of routine in German feed analysis.

The BFS content of a diet is the weighted mean of the BFS contents of its constituents:

$$\eta_{\mathrm{BFS}} = \sum \left(\eta_{\mathrm{BFS,\,i}} \cdot x_{\mathrm{i}}\right) \quad (14)$$

where

η_{BFS}	mean BFS content of a diet (in kg kg^{-1})
$\eta_{\mathrm{BFS,\,i}}$	BFS content of feed constituent i (in kg kg^{-1})
x_{i}	mass fraction of feed constituent i in the diet (in kg kg^{-1})

and

$$\sum x_{\mathrm{i}} = 1 \quad (15)$$

The dry matter (DM) intake rate results from the calculation of energy requirements. In Germany these are obtained from the metabolizable energy (ME) requirements that are calculated according to Flachowsky et al. (2006) as described in Haenel et al. (2011b).

3.2 Livestock properties

The methodology distinguishes between the following subcategories of pigs:

Sows and their litter are treated together. Energy requirements are calculated for two gravidity phases, for the lactating period and for the period between weaning and covering. The number of piglets raised, their final weight and the mean weight of the sow are taken into account.

Suckling-pigs are supplied with energy and nutrients via the sow's milk only. This milk does not contain fibre. Hence its BFS content is zero.

Weaners and finishing pigs are treated in a similar manner. Their weights and weight gains are considered as drivers for energy requirements. For details see Haenel et al. (2011b).

Boars are those mature males that are used for reproduction. The only driver in the energy demand calculations is their weight.

For an investigation in the effectiveness of phase feeding on enteric CH_4 emissions, **standard animals** were used as in Dämmgen et al. (2011b). They have properties as follows: The standard sows used in this work have a mean weight of 200 kg animal^{-1}. No weight gain is considered. 23 piglets are raised per sow per year and weaned at a weight of 8.5 kg animal^{-1}. Standard weaners have a mean weight gain of 410 g animal^{-1} d^{-1} and a final weight of 28.5 kg animal^{-1}. The number of production cycles per year takes a service and disinfection period of 8 d round^{-1} into account. Standard finishers are assumed to have a mean weight gain of 750 g animal^{-1} d^{-1} and a final weight of 110 kg animal^{-1}. Service and disinfection periods are variable. Standard boars have a mean weight of 180 kg animal^{-1}. A weight gain is not taken into account. Boars are fed sows' feed.

3.3 Composition of diets and feeding regimes in German pig production

A survey was made in 2010 and 2011 to assess the regional variation in pig feeding. As described in Dämmgen et al. (2011b), feeding experts were asked to provide typical diet compositions for the German federal states. Niedersachsen (Lower Saxony) with its high pig populations was subdivided in 11 territorial units that were uniform with respect to pig feeding. In all, 288 diets were provided, 86 for sows, 66 for weaners and 122 for finishing pigs. For sows and weaners, single and two phase feeding were investigated. Feeds for finishing pigs allowed for the consideration of single, two and three phase feeding. No special feeds for boars were reported; they are fed sow feed. In Niedersachsen, diets with reduced nitrogen contents (RAM feed [5]) are fed to some extent. The census data includes the number of animal rounds per year for each German federal state and each year from 1990 to 2009.

3.4 BFS contents of diet constituents

BFS contents of feed constituents can be extracted from the literature. For the diet constituents mentioned by the experts, the contents are listed in Table 4.

Table 4:

BFS contents of feed constituents in pig production. This Table supplements Table 1 in Dämmgen et al. (2011b).

Feed constituent		η_{BFS} kg kg^{-1}	source[1]
green meal	Grünmehl	0.270	[2]
wheat	Weizen	0.043	[1]
triticale	Triticale	0.096	[3]
rye	Roggen	0.066	[1]
barley	Gerste	0.071	[1]
oat	Hafer	0.075	[1]
CCM	CCM	0.060	[1]
maize	Mais	0.052	[1]
maize flakes	Maisflocken	0.052	[1]
millet	Hirse	0.024	[6]
linseed	Leinsamen	0.210	[3]
potato peel	Kartoffelschalen	0.167	[3]
potato chips	Kartoffelchips	0.107	[3]
cassava root meal	Maniokmehl	0.129	[1]
sugar beet pulp	Trockenschnitzel	0.664	[1]
sugar beet pulp with molasses	Melasseschnitzel	0.506	[1]
bakery waste	Backabfälle	0.159	[1]
wheat bran	Weizenkleie	0.191	[1]
rye bran	Roggenkleie	0.280	[1]
oat flakes	Haferflocken	0.079	[1]
oat bran	Haferschälkleie	0.132	[1]
wheat gluten feed	Weizenkleber	0.038	[1]
maize gluten feed	Maiskleberfutter	0.241	[1]
distillers dried grains with solubles	Weizenschlempe	0.239	[4]
maize starch	Maisstärke	0.000	[5]
maize germs	Malzkeime	0.200	[1]
apple pomace	Apfeltrester	0.260	[2]
molasses	Melasse	0.084	[1]
peanut oil	Erdnussöl	0.000	
soya oil	Sojaöl	0.000	
rape seed oil	Rapsöl	0.000	
sunflower oil	Sonnenblumenöl	0.000	

[5] RAM: Rohprotein-angepasste Mischung: mixture adjusted to crude protein demands

Continuation of Table 4:

Feed constituent		η_{BFS} kg kg^{-1}	source[1]
sugar	Zucker	0.000	[1]
peas	Erbsen	0.090	[1]
faba bean	Ackerbohne	0.079	[1]
soya bean	Sojabohne	0.152	[1]
soya protein	Sojaeiweißkonzentrat	0.000	[5]
linseed expeller	Leinexpeller	0.302	[1]
rape seed expeller	Rapsexpeller	0.213	[1]
soy pulp	Sojaschalen	0.419	[3]
rape seed extraction meal	Rapsextraktionsschrot	0.215	[1]
sunflower extraction meal	Sonnenblumen-extraktionsschrot	0.143	[6]
soya bean extraction meal 48 % XP	Sojaextraktionsschrot 48 %, getoastet	0.157	[1]
soya bean extraction meal 44 % XP	Sojaextraktionsschrot 44 %, getoastet	0.189	[1]
potato protein	Kartoffeleiweiß	0.088	[1]
sweet whey	Molke, Süß-, frisch	0.018	[1]
acid whey	Molke, Sauer-, frisch	0.095	[1]
whey protein	Molkeneiweiß, frisch	0.000	[5]
skimmed milk powder	Milchprodukte (Magermilchpulver)	0.053	[1]
whey concentrate	Molke, Süß-, getrocknet	0.003	[1]
cows' milk	Kuhmilch (Vollmilch)	0.000	[1]
fish meal 64 % XP	Fischmehl 64 % RP	0.001	[1]
yeast	Bierhefe, Weinhefe (Vinasse)	0.306	[1]
corn steep	Maisquellwasser	0.000	
fish oil	Fischöl	0.000	
lignocellulose	Lignocellulose	0.730	[2]
rice gluten feed	Reiskleber	0.038	[1]
palm butter	Pflanzenfett	0.000	
formic acid	Ameisensäure	0.000	
propionic acid	Propionsäure	0.000	
calcium phosphate	Calciumphosphat	0.000	
lime (calcium carbonate)	kohlensaurer Kalk	0.000	
sodium bicarbonate	Natriumhydrogencar-bonat	0.000	
salt	Viehsalz	0.000	

[1] Sources: [1] Kirchgeßner (2004) pp 571-578; [2] Lindermayer et al. (2009), pg 134; [3] LfL (undated); [4] Lindermayer (undated); [5] calculations using Equation (12) and data provided in Beyer et al. (2004); [6] DLG (undated)

Most data in Table 4 is taken from Kirchgeßner (2004). Some feed constituents could be extracted from lists published by LfL (Lindermayer, 2009, undated: LfL, undated) or the DLG data base Futtermittel.Net.

Properties of corn steep could be deduced from information provided by the manufacturer (Beuker, undated).

Some less frequently used feed constituents were replaced by similar constituents due to missing or inconsistent data:

- maize flakes by maize
- potato chips by steamed potatoes
- soya protein by soya beans
- soya pulp by legume seed hulls
- bakery waste by wheat second flour
- fish oil by fish juice
- rice gluten feed by wheat gluten feed

η_{BFS} for all oils and fats was set zero, as they do not contain fibre or carbohydrates. The fibre content of corn steep is very low, which justifies setting η_{BFS} to zero.

3.5 Back-calculation of gross energy related methane conversion ratio

It is good practice within emission reporting to indicate MCR according to Equation (16).

$$MCR_{i,j} = \frac{EF_{CH4,i,j} \cdot \eta_{CH4}}{GE_{i,j}} \quad (16)$$

where

$MCR_{i,j}$ methane conversion ratio for subcategory i in region j (in MJ MJ^{-1})
$EF_{CH4,i,j}$ CH_4 emission factor for subcategory i in region j (in kg place^{-1} a^{-1} CH_4)
η_{CH4} energy content of methane (η_{CH4} = 55.65 MJ (kg CH_4)$^{-1}$)
$GE_{i,j}$ gross energy intake rate for subcategory i in region j (in MJ place^{-1} a^{-1})

The German inventory uses the metabolizable energy (ME) requirements to derive feed intake. Both ME and GE contents of the diets are variables. Hence the conversion of ME to GE intake rates varies with diets. The energy equivalent of CH_4 is constant.

$$GE_{i,j} = ME_{i,j} \cdot \frac{\eta_{GE,i,j} \cdot \eta_{CH4}}{\eta_{ME,i\,j}} \quad (17)$$

where

$GE_{i,j}$ gross energy intake rate per place for subcategory i in region j (in MJ place^{-1} a^{-1})
$ME_{i,j}$ intake rate of metabolizable energy for subcategory i in region j (in MJ place^{-1} a^{-1})
$\eta_{GE,i,j}$ gross energy content of diet for subcategory i in region j (in MJ kg^{-1})
η_{CH4} energy content of methane (η_{CH4} = 55.65 MJ (kg CH_4)$^{-1}$)
$\eta_{ME,i,j}$ metabolizable energy content of diet for subcategory i in region j (in MJ kg^{-1})

The national overall *MCR* for pigs is calculated as weighted mean for sows (with litter), weaners, finishing pigs and boars.

4 Results

4.1 National mean methane emission factors and methane conversion ratios

For the years 1994, 2001 and 2007, full census data (animal numbers and farm structure survey data) were available. For the feeding regimes put into practice in the respective region and year, the CH_4 emission factors (emissions per place and year) and CH_4 conversion ratios (*MCR*) were calculated for the four standard animals, see Chapter 3.2. The results are presented in Tables 5 and 7. Table 5 shows that the application of modelled *MCR* for specific diets results in elevated emission rates for sows and boars and reduced emission rates for weaners and finishing pigs as compared to default *MCR* (previous calculations). No significant variation between the years can be observed for sows and weaners. The reduction of emission rates for finishing pigs is attributed to an increased use of phase feeding (see below).

Phase feeding has become standard during the past decades. For sows, the diet during lactation is particularly rich in *ME* and poor in fibre, the diet in the non-lactating phase is rich in fibre with comparatively lower *ME* contents. It is normal to feed weaners two different diets with a change at a weight of about 15 kg animal^{-1}. Boars are fed the same feeds as sows. In some regions, farmers prefer to feed the lactation diet, in others the non-lactating diet.

Phase feeding and the introduction of N-reduced diets have increased significantly for finishing pigs (see Dämmgen et al., 2011b). The mean properties of the diets reported (non-weighted means) exhibit a trend. As shown in Table 6, the step from two phases to three phases clearly reduces the CH_4 emission rate per place as well as *MCR*. The effect of N reduced diets may be adverse; the data shown are ambiguous.

Table 7 illustrates that *MCR* (i.e. the fraction of *GE* that is lost with CH_4) is constant with time for all four standard animals.

4.2 Regional variation of methane emission factors and methane conversion ratios

The national mean *MCR* listed in Table 7 follow from regionally diverse data that reflect regionally different diet composition and feeding regimes. Table 8 shows the variability of EF_{CH4} and *MCR* in the regions considered. For boars, the large differences result from the two diet types used. Small EF_{CH4} and *MCR* are associated with the use of lactation diets.

Table 8 also highlights the value of regional data if emission reduction measures are to be taken.

The modelled methane emission rates agree satisfactorily with those estimated from experiments, see Chapter 1.3.

Table 5:
Methane emission factors EF_{CH4}, annual national means (values for 1994, 2001 and 2007 according to Chapters 3.1 to 3.4)

	1994	2001	2007	previous calculations		unit
				modified[A]	inventory[B]	
sows (including suckling piglets)	2.20	2.22	2.23	2.08	2.13	kg place^{-1} a^{-1} CH_4
weaners	0.31	0.32	0.31	0.42	0.43	kg place^{-1} a^{-1} CH_4
finishing pigs	0.96	0.93	0.90	1.17	1.32	kg place^{-1} a^{-1} CH_4
boars	2.08	2.07	1.98	1.75	1.73	kg place^{-1} a^{-1} CH_4

[A] modified diets and feeding strategies as in Dämmgen et al. (2011b), but use of IPCC (1996) default *MCR* of 6 kJ MJ-1.
[B] using the methodology described in Rösemann et al. (2011) with constant feed and feeding strategies

Table 6:
Finishing pigs, methane emission factors EF_{CH4} and methane conversion ratios *MCR* as a function of feeding strategy (2007 data set) (non-weighted means) (duration of service time: 5 d round^{-1})

Feed type[A]	1	2S	2R	3S	3R	unit
EF_{CH4}	1.04	0.97	1.03	0.82	0.79	kg place^{-1} a^{-1} CH_4
MCR	5.3	4.8	5.2	4.2	4.0	kJ MJ^{-1}

[A] 1: single phase feeding; 2S: two phase feeding, standard diet; 2R: two phase feeding, N and P reduced diet; 3S: three phase feeding, standard diet; 3R: three phase feeding, N and P reduced diet

Table 7:
Methane conversion ratios *MCR*, annual national means

	1994	2001	2007	previous calculations		unit
				modified [A]	inventory [B]	
sows (including suckling piglets)	6.3	6.4	6.4	6.0	6.0	kJ MJ^{-1}
weaners	4.3	4.4	4.4	6.0	6.0	kJ MJ^{-1}
finishing pigs	4.6	4.7	4.6	6.0	6.0	kJ MJ^{-1}
boars	7.1	7.1	7.0	6.0	6.0	kJ MJ^{-1}
average pigs [C]	4.6	4.8	4.7	6.0	6.0	kJ MJ^{-1}

[A] modified diets and feeding strategies as in Dämmgen et al. (2011b), but use of IPCC (1996) default *MCR* of 6 kJ MJ-1.
[B] using the methodology described in Rösemann et al. (2011) with constant diet composition and feeding strategies
[C] weighted mean taking animal populations (Rösemann et al., 2011) into account

Table 8:
Regional variation of methane emission factors EF_{CH4} and methane conversion ratios *MCR* (results for 2007)

Region	EF_{CH4} kg $place^{-1}$ a^{-1}				*MCR* kJ MJ^{-1}			
	sows[A]	weaners	finishers	boars	sows[A]	weaners	finishers	boars
01	2.50	0.30	0.96	2.49	7.2	4.2	4.8	8.6
02	2.48	0.36	0.99	2.24	7.1	5.0	5.1	7.6
03	2.56	0.29	0.94	2.48	7.3	4.2	4.8	8.2
04	2.53	0.31	0.86	2.38	7.0	4.4	4.4	7.9
05	2.68	0.32	0.94	1.98	7.7	4.4	4.9	7.0
06	2.33	0.34	0.92	2.14	6.8	4.7	4.7	7.4
07	2.47	0.30	0.98	2.13	7.1	4.3	4.9	7.4
08	2.24	--- [B]	0.71	1.16	6.5	--- [B]	3.7	4.2
09	2.74	0.30	0.91	2.13	7.9	4.2	4.6	7.4
10	2.37	0.29	0.76	1.29	6.9	4.0	3.9	4.5
11	2.74	0.30	0.96	2.13	7.9	4.2	4.8	7.4
12	2.65	0.30	0.83	1.34	7.5	4.2	4.0	4.6
13	2.34	0.31	0.95	1.30	6.8	4.4	4.8	4.6
14	2.51	0.30	1.01	2.53	7.2	4.2	5.1	8.8
15	--- [B]	0.35	0.91	2.00	--- [B]	4.8	4.6	7.0
16	2.61	0.30	0.98	2.41	7.5	4.3	4.9	7.9
17	2.45	0.31	0.98	2.14	7.0	4.4	5.0	7.2
18	2.05	0.28	0.88	1.29	5.8	3.9	4.4	8.2
19	2.73	0.30	1.05	2.32	7.8	4.2	5.3	7.5
20	2.40	0.28	0.90	1.28	6.9	4.0	4.6	4.5
minimum	2.05	0.28	1.05	2.53	5.8	3.9	3.7	4.2
maximum	2.74	0.36	0.71	1.16	7.9	5.0	5.3	8.8
mean[C]	2.49	0.31	0.93	1.90	7.1	4.4	4.6	7.1

[A] including suckling pigs
[B] value omitted as outlier
[C] weighted mean taking animal populations (Rösemann et al., 2011) into account

5 Conclusions

Even though CH_4 emissions from pigs' enteric fermentation do not form a key category in the emission inventory, they can now be treated with a state of the art methodology. The experimental data available and the model approaches deduced from them allow for a detailed treatment.

As the effort to perform a Tier 3 approach as described here may not be justified elsewhere, a set of adequate *MCR* can be provided at least for Northwest European conditions. The following values are proposed (see Table 8):

- sows with litter 7.1 kJ MJ^{-1}
- weaners 4.4 kJ MJ^{-1}
- finishing pigs 4.6 kJ MJ^{-1}
- boars for reproduction 7.1 kJ MJ^{-1}

If no differentiation between subcategories is possible, a *MCR* of 5 kJ MJ^{-1} is considered adequate. (This mean is depending on the respective shares of animal subcategories. The German weighted mean for 2010 amounts to 4.8 kJ MJ^{-1}.)

For Germany and 2010, the application of the *MCR* listed in Table 8 results in an emission reduction of about 15 %, i.e. about 4.0 Gg a^{-1} CH_4 or 100 Gg a^{-1} CO_2 equivalents [6].

[6] using a global warming potential GWP_{CH4} of 25 kg kg^{-1} CO_2-eq according to Solomon et al. (2007)

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