Improved national calculation procedures to assess energy requirements, nitrogen and VS excretions of dairy cows in the German emission model GAS-EM

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Summary

The calculation module for the assessment of feed intake and excretion rates of dairy cows in the German agricultural emission model GAS-EM is described in detail. The module includes the description of methane emissions from enteric fermentation as well as the assessment of volatile solids and (renal and faecal) nitrogen excretions responsible for carbon and nitrogen species emissions from manure management. Input parameters are milk yield and composition, weight and weight gain as well as feed properties.

The model is based on the derivation of energy requirements and the limitation on dry matter intake. The results agree well with those obtained from regression models and respective experiments.

The model is able to reflect national and regional peculiarities in dairy cow husbandry. It is an adequate tool for the establishment of emission inventories and for the construction of scenarios for policy advice.

Keywords: Dairy cows, model, energy balance, mass balance, methane, nitrogen, emission, inventory

Zusammenfassung

Verbesserte Rechenverfahren zur Bestimmung von Energie-Bedarf, Stickstoff- und VS-Ausscheidungen von Milchkühen im deutschen Emissionsmodell GAS-EM

Das Rechenmodul zur Bestimmung der Futteraufnahme und der Ausscheidungsraten von Milchkühen im deutschen landwirtschaftlichen Emissionsmodell GAS-EM wird ausführlich beschrieben. Es ist in der Lage, die Methan-Emissionen aus der Verdauung sowie die zur Berechnung der Emissionen von Methan und den Stickstoff-Verbindungen benötigten Ausscheidungen von Kohlenstoff („volatile solids“) und Stickstoff (renal und fäkal) aus dem Wirtschaftsdünger-Management zu berechnen. Als Eingangsgrößen werden Milchmenge und Milchzusammensetzung, Gewicht und Gewichtszunahme sowie Futtereigenschaften benötigt.

Das Modell basiert auf der Ableitung des Energiebedarfs und der Limitierung der Trockenmasseaufnahme. Die Ergebnisse stimmen mit denen aus Regressionsmodellen und den ihnen zugrunde liegenden Messungen überein.

Das Modell erlaubt eine Berücksichtigung der nationalen und regionalen Besonderheiten in der Milchkuh-Haltung. Es ist daher als Instrument zur Berechnung von Emissionsinventaren sowie zur Erstellung von Szenarien zur Politikberatung geeignet.

Schlüsselwörter: Milchkühe, Modell, Energiehaushalt, Stoffhaushalt, Methan, Stickstoff, Emission, Inventar

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1 Introduction

In Northwest and Central Europe, emissions of gaseous pollutants from agriculture are dominated by emissions from animal husbandry. The most important key source is dairy cattle, so any measures to reduce emissions have to consider dairy cattle as a priority. Emission reduction strategies which consider both the necessity of agricultural production and its particular features have to rely on models that describe the emitting processes adequately. With respect to dairy cattle, the processes that emit methane (CH_4) from enteric fermentation as well as CH_4, ammonia (NH_3), nitrous and nitric oxides (N_2O and NO) from manure management have to be reproduced. Due to geographic and historical reasons, dairy cattle husbandry in Northwest and Central Europe exhibits regional variations in the characteristics of production that should be reflected in emission modelling. However, the models provided in the guidance documents of the Intergovernmental Panel on Climate Change (IPCC) and the UNECE Convention on Long-Range Transboundary Air Pollution do not provide methods that can adequately reflect those variations. The assessment of the emissions of greenhouse gases as described in the IPCC (2006) methodology reflects animal performance to some extent; it does not consider feed properties. The modelling of emissions of nitrogen (N) species from manure management presupposes an adequate assessment of N excretion in both faeces and urine. This cannot be achieved by the IPCC (2006) methodology (IPCC, 2006, pg. 10.57 ff) as it presupposes knowledge of the N intake in feed. The UNECE methodology (EMEP, 2006, pg. B1090-16) does not provide a procedure to quantify N excretion rates.

The module currently describing dairy cattle in the German agricultural emission model GAS-EM is inconsistent as it describes the emissions of CH_4 from enteric fermentation and manure management using a modified IPCC approach (IPCC, 2006, see Dämmgen et al., 2009a). However, the description of the emission of N species relies on N excretions assessed by the DIAS model (Kristensen et al., 1998).

Both models quantify the energies involved, but the results differ in principle. The IPCC model aims at a description of animals *fed as required* with regard to energy, whereas the DIAS model is based on *actual feeding* data obtained from surveys. As the improved GAS-EM dairy cow module CDC09 is to be coupled with land use data, it has to adopt the current German units describing feed properties, in particular the net energy for lactation (NEL). In addition, it has to be consistent with the feeding recommendations provided by GfE (2001).

Furthermore, the assessment of CH_4 emissions from enteric fermentation as well as VS excretion makes use of IPCC default factors to derive gross energy (GE) intakes from metabolizable energy (ME) intakes. Again, a national (NEL based) approach would be desirable.

Thus, the intention of this paper is to provide a harmonized methodology for the assessment of the excretion of both carbon (C) and N in order to calculate the emissions of C and N species in dairy cattle husbandry using the same data set. At the same time, an improvement of the quality of input parameters such as milk yield, animal weight and grazing times is to be achieved. This will be dealt with in a companion paper.

2 Methodological changes and improvements

2.1 Inconsistencies and lack of detail

German emission reporting for dairy cattle relied on the IPCC (2006) methodology for the description of CH_4 emissions and on N excretion data obtained from the DIAS model as described by Kristensen et al. (1998).

A major prerequisite for assessing excretions is the adequate description of energy requirements and restricting entities such as dry matter (DM) intake. Here, the two models used different approaches. Both models could not reflect German feeding practices to the degree desirable.

In some respects, the IPCC model to derive emissions from enteric fermentation and VS excretion rates does not appear to reflect physiological requirements, i.e. in deriving the energy requirements for pregnancy from the animal weight rather than the development of the conception product and the additional energy requirement for maintenance of the mother.

When incorporated into the German emission model GAS-EM in 2005, the DIAS model differed from the other model descriptions available in principle. Whereas the other models used simple methods to derive total N excretions (i.e. the sum of faecal and renal N) from linear regressions using one or few parameters, the DIAS model considered energies needed as well as feed intake during grazing and allowed for the assessment of faecal N, from which the TAN (total ammoniacal nitrogen) contents of excreta could be obtained (Dämmgen and Lüttich, 2005). The knowledge of TAN is a prerequisite to quantify emissions of N species using a mass flow approach (Dämmgen and Hutchings, 2008; Reidy et al., 2008).

The DIAS model was developed to describe the Danish situation. In contrast to other modules within GAS-EM, it does not reflect feeding to requirements (as postulated within IPCC) but rather the actual Danish feeding practice. The model uses Scandinavian Feed Units throughout. These cannot be "translated" into SI units directly. In the DIAS model, input variables for feed differentiate between grazing, roughage fed indoors and concentrates, using

Danish standard values for each of them. As the future module is to be part of integrated assessment studies which include regionally specific feed supply with varying diet components, etc., a module fully compatible with IPCC and UNECE standards was to be developed that used SI units throughout. The latter is a practical prerequisite as the respective German data bases describing feed and animals (DLG, 1997; KTBL, 2006; Beyer et al., undated) strictly use SI units.

The DIAS model as used in GAS-EM was unable to reflect the different feeding practices in typical grassland regions and the other regions, where a mixed diet (containing maize silage as a major component) is fed.

2.2 Preliminary remarks and definitions

2.2.1 Overview

As animal performance presupposes an adequate energy intake, the first step towards an improved model is the assessment of the net energy requirements, the second the calculation of the resulting feed intake and the third the derivation of VS and N excretions. The methods derived will be applied to standard cows and standard feeds to illustrate congruencies and differences.

A companion paper will deal with the different feeding regimes in Germany and their identification (Dämmgen et al., 2009b).

2.2.2 Notation

It is necessary to differentiate between annual, actual daily and mean daily entities. Therefore, it was decided to characterize them with different symbols as follows:

Annual data will be written in upper case letters, daily data in lower case letters. Actual daily data will be identified by an asterisk, mean daily data by plain symbols, e.g.

DM annual amount of DM intake (kg cow^{-1} a^{-1} DM)
dm^* actual daily amount of DM intake (kg cow^{-1} d^{-1} DM)
dm mean daily amount of DM intake (kg cow^{-1} d^{-1} DM)

Symbols for entities used frequently are
m mass of nitrogen
NEL amount of NEL
t time
w animal weight
x, X fraction

Constants and coefficients are normally used in an alphabetical order. A full caption is provided for each equation.

3 Energy requirements and DM intake

IPCC (2006) as well as the relevant German and US bodies (GfE, 2001; BNAR, 2001) deduce energy requirements from the net energy requirements. These are themselves obtained from the partial net energy requirements for maintenance, for obtaining feed, for lactation, pregnancy, growth and work (draft power) that are then summed to yield the total net energy requirements.

3.1 The NEL approach

In order to analyze feed requirements and to characterize feed properties, Austria, Germany and Switzerland (Gruber et al., 2004), Belgium, the Czech Republic, France, Hungary, Italy, the Netherlands (Smink et al., 2005), Slovakia and the USA (BNAR, 2001, pg. 13 ff) use the NEL approach where NEL means net energy for lactation. Irrespective of the literal meaning of the words, the net energy for lactation concept expresses the net energies for all processes in this unit.

3.2 NEL requirements

In analogy with the IPCC (2006) methodology, the overall NEL requirements are expressed by Equation (1):

$$NEL_{tot} = \alpha \cdot \begin{pmatrix} nel_m + nel_f + nel_{lc} \\ + nel_d + nel_p + nel_g \end{pmatrix} \quad (1)$$

where
NEL_{tot} annual NEL required (MJ cow^{-1} a^{-1} NEL)
α time units conversion factor (α = 365 d a^{-1})
nel_m NEL required for maintenance (MJ cow^{-1} d^{-1} NEL)
nel_f NEL needed to obtain food (MJ cow^{-1} d^{-1} NEL)
nel_{lc} NEL for lactation (MJ cow^{-1} d^{-1} NEL)
nel_d NEL required for draft power (MJ cow^{-1} d^{-1} NEL)
nel_p NEL required for pregnancy (MJ cow^{-1} d^{-1} NEL)
nel_g NEL consumed for growth (MJ cow^{-1} d^{-1} NEL)

3.2.1 NEL requirement for maintenance

NEL requirements for maintenance are obtained using Equation (2) (GfE, 2001, pg. 20):

$$nel_m = a \cdot w_{unit} \cdot \left(\frac{w}{w_{unit}} \right)^{0.75} \quad (2)$$

where

nel_m net energy required for maintenance (MJ cow^{-1} d^{-1} NEL)
a constant (a = 0.364 MJ kg^{-1} d^{-1} NEL)
w_{unit} animal weight unit (w_{unit} = 1 kg cow^{-1})
w animal weight (kg cow^{-1})

In GfE, Equation (2) uses a coefficient α_{GfE} = 0.293 MJ kg^{-1} d^{-1} NEL to derive nel_m from animal weights. However, it could be shown that this is inadequate and underestimates nel_m considerably. Agnew et al. (2003) and Kebreab et al. (2003) suggest that the factor in the respective equation for ME_m be 0.62 MJ kg^{-1} d^{-1} ME. This can be translated into a coefficient for nel_m of 0.364 MJ kg^{-1} d^{-1} NEL. This factor is used in CDC09: α_{CDC09} = 0.364 MJ kg^{-1} d^{-1} NEL.(1)

3.2.2 NEL requirement to obtain feed

IPCC (2006), pg. 10.16 provides an approach to estimate the NE requirements for activity (i. e. to obtain feed) as proportional to the NE requirements for maintenance. This approach can immediately be rewritten in NEL terms to be used in CDC09. Taking formally into account separate contributions by housing and grazing one arrives at

$$nel_f = \left(c_{house} \cdot \left(1 - \frac{\tau_{pasture}}{\alpha} \right) + c_{pasture} \cdot \frac{\tau_{pasture}}{\alpha} \right) \cdot nel_m \quad (3)$$

where

nel_f NEL needed to obtain feed (in analogy to IPCC) (MJ cow^{-1} d^{-1} NEL)
c_{house} coefficient for housing (c_{house} = 0.00; IPCC(2006)-10.17, Table 10.5)
$\tau_{pasture}$ duration of grazing time (d a^{-1})
α time units conversion factor (α = 365 d a^{-1})
$c_{pasture}$ coefficient for pasture ($c_{pasture}$ = 0.17; IPCC(2006)-10.17, Table 10.5)
nel_m NEL required for maintenance (in analogy to IPCC) (MJ cow^{-1} d^{-1} NEL)

3.2.3 NEL requirements for lactation

In contrast to IPCC (2006), the approach proposed includes the energy requirements for the synthesis of milk protein (GfE, 2001, pg. 21f):

$$nel_{lc} = y_m \cdot \begin{pmatrix} c_{lact\,1,\,GfE} + c_{lact\,2,\,GfE} \cdot x_{fat} \\ + c_{lact\,3,\,GfE} \cdot x_{MP} + d \end{pmatrix} \cdot a \quad (4)$$

where

nel_{lc} net energy requirements for lactation (MJ cow^{-1} d^{-1} NEL)
y_m milk yield (kg cow^{-1} d^{-1})
$c_{lact\,1,\,GfE}$ constant ($c_{lact\,1,\,GfE}$ = 0.95 MJ kg^{-1})
$c_{lact\,2,\,GfE}$ coefficient ($c_{lact\,2,\,GfE}$ = 38 MJ kg^{-1})
x_{fat} mass fraction of fat (kg kg^{-1})
$c_{lact\,3,\,GfE}$ coefficient ($c_{lact\,3,\,GfE}$ = 21 MJ kg^{-1})
x_{MP} mass fraction of milk protein (kg kg^{-1})
d constant (d = 0.1 MJ kg^{-1} NEL)
a correction factor (a = 1 MJ MJ^{-1} NEL for daily data and 1.04 MJ MJ^{-1} NEL for annual mean data)

In GfE (2001), the application of Equation (4) presupposes the knowledge of daily milk yields and milk constituents. However, these vary with time (see Figure 1).

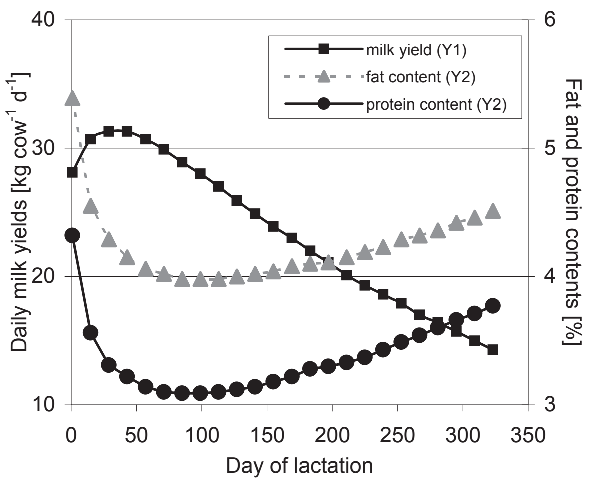

Figure 1:

Typical time series of daily milk yields and milk fat and protein contents (redrawn after Greimel and Steinwidder, 1998)

Exemplary model calculations indicate that the use of mean daily milk yields and constituent concentrations instead of actual data requires a correction factor $a \neq 1$.

(1) In principle, the NEL system does not demand that metabolizable energies, ME and NEL be interconverted. However, the NEL approach documented in GfE (2001) does not include the NEL requirements for grazing. Since the extent to which cattle obtain feed by grazing varies regionally, it is desirable to account for the consequent energy demand. As this is a minor constituent of the total NEL requirements, the conversion from NEL to ME proposed by van Es (1975) (see GfE, 2001, pg. 19) is used:

$$ME = \frac{NEL}{a + b \cdot X_{ME}}$$

where

NEL net energy for lactation (MJ NEL)
ME metabolizable energy (MJ ME)
α constant (α = 0.4632)
b constant (b = 0.24)
X_{ME} metabolizability (assumed: X_{ME} = 0.60 MJ MJ^{-1})

3.2.4 NEL requirements for pregnancy

The GfE (2001), pg. 23, methodology provides absolute figures derived from the energy used for the development of the conception products and the udder:

$$NEL_{\mathrm{p}}^{*} = NEL_{\mathrm{cp}}^{*} + NEL_{\mathrm{u}}^{*} \quad (5)$$

where
- $NEL_{\mathrm{p}}*$ actual net energy required for pregnancy (MJ calf^{-1})
- $NEL_{\mathrm{cp}}*$ actual net energy required for the development of the uterus including the conception product (MJ calf^{-1})
- $NEL_{\mathrm{u}}*$ actual net energy required for the development of the udder (MJ calf^{-1}) $NEL_{\mathrm{u}}* = 31$ MJ calf^{-1} d^{-1} (GfE, 2001, pg.23)

The net energy lactation for the development of the conception product is a function of the daily growth rate:

$$NEL_{\mathrm{cp}}^{*} = \sum_{\tau_{\mathrm{p}}=1}^{\tau_{\mathrm{p,\,fin}}} a \cdot w_{\mathrm{calf}} \cdot e^{\mathrm{b} \cdot \tau_{\mathrm{p}}} \quad (6)$$

where
- $NEL*_{\mathrm{cp}}$ actual NEL required for the development of the conception product (MJ calf^{-1})
- a constant (a = 0.000122 MJ kg^{-1} d^{-1})
- w_{calf} birth weight of calf (kg calf^{-1})
- b constant (b = 0.0165)
- τ_{p} day after conception
- $\tau_{\mathrm{p,\,fin}}$ day of birth ($\tau_{\mathrm{p,\,fin}}$ = 279)

As calf weights are not available on a national scale in Germany, a standard calf weight of 36 kg calf^{-1} is assumed. In this case, $NEL_{\mathrm{cp}}*$ and $NEL_{\mathrm{u}}*$ add up to overall $NEL_{\mathrm{p}}*$ requirements of 917 MJ calf^{-1}, independent of the calf's or the mother's weight.(2)

The GfE approach is used in CDC09.

Again, the daily NEL requirement for the development of the conception product, nel_{p}, is then calculated from $NEL_{\mathrm{p}}*$ as a function of the interval between calvings according to

$$nel_{\mathrm{p}} = \frac{NEL_{\mathrm{p}}^{*}}{t_{\mathrm{ibc}}^{*}} \quad (7)$$

where
- nel_{p} NEL required for pregnancy (MJ cow^{-1} d^{-1} NEL)
- $NEL_{\mathrm{p}}*$ NEL required for pregnancy ($NEL_{\mathrm{p}}*$ = 917 MJ calf^{-1} NEL)
- $t_{\mathrm{ibc}}*$ absolute duration of interval between calvings (d calf^{-1})

3.2.5 NEL requirements for growth

GfE (2001), pg. 22, relate the NEL requirements for growth to the weight gain per year. This approach is also used in CDC09.

$$nel_{\mathrm{g,\,GfE}} = \frac{a \cdot \Delta w}{\alpha} \quad (8)$$

where
- $nel_{\mathrm{g,\,GfE}}$ NEL required for growth (MJ cow^{-1} d^{-1})
- a constant (a = 25.5 MJ kg^{-1} NEL)
- Δw weight gain (kg cow^{-1} a^{-1})
- α time units conversion factor (α = 365 d a^{-1})

3.3 Linking feed intake with energy requirements

If an animal is fed according to requirements, the net energy requirements (NEL_{tot}) have to be met by the net energy for lactation provided in feed (NEL_{feed}):

$$NEL_{\mathrm{feed}} = NEL_{\mathrm{tot}} \quad (9)$$

Feed will be supplied in concentrates and roughage inside the animal house and during grazing. The respective shares are also governed by the DM intake of the animals, as DM intake is limited. Once the DM intake and the feed properties are known, the intakes of GE, DE, ME, NEL and N can be deduced.

3.3.1 Treatment of DM intake

DLG (1986) provides a model of dry matter intake. DLG (2006) provides an alternative and much more detailed approach, but demands input data which are not available at the spatial and temporal scales used for inventory construction.

The methodology adopted for CDC09 differentiates between the DM intakes during lactation and during the dry period:

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(2) The mean duration of pregnancy is 279 d. Thus an amount equal to 266 MJ calf^{-1} NEL results for the development of calf and uterus. GfE (2001), pg. 23, recommend for the NEL required for the udder during the last weeks of pregnancy 13 MJ calf^{-1} d^{-1} NEL for weeks 6 to 4 before calving, as well as 18 MJ calf^{-1} d^{-1} for the final three weeks before calving which results in 651 MJ calf^{-1} NEL. Thus, the energy requirements for conception products and the development of the udder add up to 917 MJ calf^{-1} NEL .

$$DM = DM_{\mathrm{lact}} + DM_{\mathrm{dry}} \tag{10}$$

where

- DM total intake of DM (kg cow^{-1} a^{-1} DM)
- DM_{lact} intake of DM during the lactation period (kg cow^{-1} a^{-1} DM)
- DM_{dry} intake of DM during the dry period (kg cow^{-1} a^{-1} DM)

and

$$DM_{\mathrm{lact}} = DM_{\mathrm{conc,\,lact}} + DM_{\mathrm{rough,\,lact}} = \left(dm_{\mathrm{conc,\,lact}} + dm_{\mathrm{rough,\,lact}}\right)\cdot t_{\mathrm{lact}} \tag{11}$$

$$DM_{\mathrm{dry}} = DM_{\mathrm{conc,\,dry}} + DM_{\mathrm{rough,\,dry}} = \left(dm_{\mathrm{conc,\,dry}} + dm_{\mathrm{rough,\,dry}}\right)\cdot t_{\mathrm{dry}} \tag{12}$$

where

- DM_{lact} annual intake of DM during the lactation period (kg cow^{-1} a^{-1} DM)
- $DM_{\mathrm{conc,\,lact}}$ annual intake of DM during the lactation period with concentrates (kg cow^{-1} a^{-1} DM)
- $DM_{\mathrm{rough,\,lact}}$ annual intake of DM during the lactation period with roughage (kg cow^{-1} a^{-1} DM)
- $dm_{\mathrm{conc,\,lact}}$ daily intake of DM during the lactation period with concentrates (kg cow^{-1} d^{-1} DM)
- $dm_{\mathrm{rough,\,lact}}$ daily intake of DM during the lactation period with roughage (kg cow^{-1} d^{-1} DM)
- t_{lact} duration of the lactation period (d a^{-1})
- DM_{dry} annual intake of DM during the dry period (kg cow^{-1} a^{-1} DM)
- $DM_{\mathrm{conc,\,dry}}$ annual intake of DM during the dry period with concentrates (kg cow^{-1} a^{-1} DM)
- $DM_{\mathrm{rough,\,dry}}$ annual intake of DM during the dry period with roughage (kg cow^{-1} a^{-1} DM)
- $dm_{\mathrm{conc,\,dry}}$ daily intake of DM during the dry period with concentrates (kg cow^{-1} d^{-1} DM)
- $dm_{\mathrm{rough,\,dry}}$ daily intake of DM during the dry period with roughage (kg cow^{-1} d^{-1} DM)
- t_{dry} duration of the dry period (d a^{-1})

The assessment of the respective entities is described in the following chapters. The duration of the lactation and dry periods is calculated in Chapter 6.1.1.3.

3.3.1.1 DM intake during lactation

The daily amount of DM intake during the lactation period can be described according to the procedure proposed by DLG (1986) and subsequently modified (see Spiekers et al., 2006):

$$dm_{\mathrm{rough,\,lact}} = a\cdot w + b\cdot\left(\frac{X_{\mathrm{NEL,\,rough,\,lact}}}{X_{\mathrm{NEL,\,rough,\,ref}}}\right)^{c} - d\cdot dm_{\mathrm{conc,\,lact}}^{2} + f\cdot\max\left(y_{\mathrm{ECM}} - e; 0\right) \tag{13}$$

where

- $dm_{\mathrm{rough,\,lact}}$ daily DM intake in roughage during lactation (kg cow^{-1} d^{-1} DM)
- a constant (a = 0.006 d^{-1})
- w animal weight (kg cow^{-1})
- b constant (b = 0.19 kg cow^{-1} d^{-1})
- $X_{\mathrm{NEL\ rough,\,lact}}$ NEL content of roughage (MJ kg^{-1} NEL)
- $X_{\mathrm{NEL,\,rough,\,ref}}$ reference NEL content of roughage ($X_{\mathrm{NEL,\,rough,\,ref}}$ = 1 MJ kg^{-1} NEL)
- c exponent (c = 2.16)
- d constant (d = 0.026 kg^{-1} cow a)
- $dm_{\mathrm{conc,\,lact}}$ daily DM intake in concentrates during lactation (in kg cow^{-1} d^{-1} DM)
- y_{ECM} milk yield (energy corrected) (kg cow^{-1} d^{-1})
- e constant (e = 25 kg cow^{-1} d^{-1})
- f constant (f = 0.1)

$X_{\mathrm{NEL,\,rough,\,lact}}$ is the weighted mean of the NEL contents of the roughage fed.

It should be noted that the results obtained with this equation are still consistent with DLG (2006) (see Gruber et al., 2006).

3.3.1.2 Energy intake and net energy requirements during lactation

The intake of net energy for lactation during the lactation period can be described as in Equation (14):

$$dm_{\mathrm{rough,\,lact}}\cdot X_{\mathrm{NEL,\,rough,\,lact}} + dm_{\mathrm{conc,\,lact}}\cdot X_{\mathrm{NEL,\,conc,\,lact}} = \frac{NEL_{\mathrm{lact}}}{t_{\mathrm{lact}}} \tag{14}$$

where

- $dm_{\mathrm{rough,\,lact}}$ daily DM intake in roughage during lactation (kg cow^{-1} d^{-1} DM)
- $X_{\mathrm{NEL\ rough,\,lact}}$ NEL content of roughage during lactation (MJ kg^{-1} NEL)
- $dm_{\mathrm{conc,\,lact}}$ daily DM intake in concentrates during lactation (kg cow^{-1} d^{-1} DM)

$X_{\text{NEL conc, lact}}$	NEL content of concentrates during lactation (MJ kg^{-1} NEL)
NEL_{lact}	net energy input required during the lactation period (MJ cow^{-1} a^{-1} NEL)
t_{lact}	duration of the lactation period (d a^{-1})

3.3.1.3 Combining DM intake and energy requirements during lactation

Equations (13) and (14) are two relations for the two unknowns $dm_{\text{rough, lact}}$ and $dm_{\text{conc, lact}}$. The solution of this set of equations requires a rearrangement of Equation (14):

$$dm_{\text{rough, lact}} = \frac{\frac{NEL_{\text{lact}}}{t_{\text{lact}}} - dm_{\text{conc, lact}} \cdot X_{\text{NEL, conc, lact}}}{X_{\text{NEL, rough, lact}}} \qquad (15)$$

Combining Equations (13) and (15) and rearranging into a standard form for second order equations yields

$$\frac{NEL_{\text{lact}}}{t_{\text{lac}} \cdot X_{\text{NEL, rough, lact}}} - dm_{\text{conc, lact}} \cdot \frac{X_{\text{NEL, conc, lact}}}{X_{\text{NEL, rough, lact}}} - a \cdot w - b \cdot \left(\frac{X_{\text{NEL, rough, lact}}}{X_{\text{NEL, rough, ref}}}\right)^{c} + d \cdot dm^{2}_{\text{conc, lact}} - f \cdot \max\left(y_{\text{ECM}} - e; 0\right) = 0 \qquad (16)$$

which is equivalent to

$$dm^{2}_{\text{conc, lact}} + B \cdot dm_{\text{conc, lact}} + C = 0 \qquad (17)$$

with

$$B = -\frac{X_{\text{NEL, conc, lact}}}{X_{\text{NEL, rough, lact}}} \cdot \frac{1}{d} \qquad (18)$$

and

$$C = \left(\frac{NEL_{\text{lact}}}{t_{\text{lac}} \cdot X_{\text{NEL, rough, lact}}} - a \cdot w - b \cdot \left(\frac{X_{\text{NEL, rough, lact}}}{X_{\text{NEL, rough, ref}}}\right)^{c} - f \cdot \max\left(y_{\text{ECM}} - e; 0\right) \right) \cdot \frac{1}{d} \qquad (19)$$

The meaningfull solution of this equation is

$$dm_{\text{conc, lact}} = -\frac{B}{2} - \sqrt{\left(\frac{B}{2}\right)^{2} - C} \qquad (20)$$

Inserting $dm_{\text{conc, lact}}$ into Equation (15) yields $dm_{\text{rough, lact}}$.

3.3.1.4 NEL requirements during the dry period

In analogy to the DM intake, the NEL intake is considered separately for the lactation and dry periods:

$$NEL_{\text{tot}} = NEL_{\text{lact}} + NEL_{\text{dry}} \qquad (21)$$

where

NEL_{tot}	annual total net energy requirements (MJ cow^{-1} a^{-1} NEL)
NEL_{lact}	annual net energy requirements during the lactation period (MJ cow^{-1} a^{-1} NEL)
NEL_{dry}	annual net energy requirements during the dry period (MJ cow^{-1} a^{-1} NEL)

At present, the information available from GfE (2001) does not allow for the variation in animal weight and the length of the dry period. However, from Table 1.4.3 in GfE (2001) an estimate of the actual amount of NEL^{*}_{dry} can be derived. According to this data set, mean NEL requirements for weeks 6 to 4 before birth are 50.6 MJ cow^{-1} d^{-1} NEL. For the final three weeks of pregnancy, NEL requirements are 55.6 MJ cow^{-1} d^{-1} NEL.

Thus, the overall actual requirement can be deduced as:

$$NEL^{*}_{\text{dry}} = t^{*}_{\text{dry}} \cdot \frac{a+b}{2} \qquad (22)$$

where

NEL_{dry}*	actual NEL requirements during the dry period (MJ cow^{-1} NEL)
t_{dry}*	actual duration of the dry period (d)
a	constant (a = 50.6 MJ cow^{-1} d^{-1})
b	constant (b = 55.6 MJ cow^{-1} d^{-1})

Hence, annual and daily requirements are, respectively,

$$NEL_{\text{dry}} = t_{\text{dry}} \cdot \frac{a+b}{2} \qquad (23)$$

$$nel_{\text{dry}} = \frac{NEL_{\text{dry}}}{t_{\text{dry}}} \qquad (24)$$

where

NEL_{dry}	annual NEL requirements during the dry period (MJ cow^{-1} a^{-1} NEL)
t_{dry}	annual duration of the dry period (d)
a	constant (a = 50.6 MJ cow^{-1} d^{-1} NEL)
b	constant (b = 55.6 MJ cow^{-1} d^{-1} NEL)
nel_{dry}	daily NEL requirements during the dry period (MJ cow^{-1} d^{-1} NEL)

3.3.1.5 DM intake during the dry period

DM intake during the dry period is defined by Equation (12).

In CDC09, the daily DM intake with concentrates, $dm_{\text{conc, dry}}$, is assumed to be 1 kg cow^{-1} d^{-1} fresh matter; the DM content is constant and 0.88 kg kg^{-1}.

Given $dm_{\text{conc, dry}}$, the balance of daily NEL requirements and NEL contents in the feed can be rearranged to yield the daily DM intake with roughage:

$$dm_{\text{rough, dry}} = \frac{nel_{\text{dry}} - dm_{\text{conc, dry}} \cdot X_{\text{NEL, conc}}}{X_{\text{NEL, rough}}} \qquad (25)$$

where

$dm_{\text{rough, dry}}$	daily intake of DM during the dry period with roughage (kg cow^{-1} d^{-1} DM)
nel_{dry}	mean daily NEL intake feed during the dry period (MJ cow^{-1} d^{-1} NEL)
$dm_{\text{conc, dry}}$	daily intake of DM during the dry period with roughage (kg cow^{-1} a^{-1} DM)
$X_{\text{NEL, conc}}$	NEL content of concentrates during the dry period (MJ kg^{-1} NEL)
$X_{\text{NEL, rough}}$	NEL content of roughage during the dry period (MJ kg^{-1} NEL)

The assessment of the annual intake of DM with concentrates and roughage presupposes the knowledge of the annual duration of the dry period:

$$DM_{\text{conc, dry}} = dm_{\text{conc, dry}} \cdot t_{\text{dry}} \qquad (26)$$

likewise

$$DM_{\text{rough, dry}} = dm_{\text{rough, dry}} \cdot t_{\text{dry}} \qquad (27)$$

where

$DM_{\text{conc, dry}}$	annual intake of DM during the dry period in concentrates (kg cow^{-1} a^{-1} DM)
$dm_{\text{conc, dry}}$	daily intake of DM during the dry period in concentrates (kg cow^{-1} d^{-1} DM)
t_{dry}	duration of the dry period (d a^{-1})
$DM_{\text{conc, dry}}$	annual intake of DM during the dry period in concentrates (kg cow^{-1} a^{-1} DM)
$dm_{\text{rough, dry}}$	daily intake of DM during the dry period in roughage (kg cow^{-1} d^{-1} DM)

3.3.2 Intake during grazing and in housing

The shares of DM intake in roughage consumed indoors and during grazing are assumed to be proportional to the respective shares in time spent indoors and grazing. Time spent in the dairy parlour is considered as time without feeding roughage.

$$DM_{\text{rough}} = DM_{\text{rough, house}} + DM_{\text{rough, graz}} \qquad (28)$$

$$\frac{DM_{\text{rough, house}}}{DM_{\text{rough, graz}}} = \frac{t_{\text{house}}}{t_{\text{graz}}} \qquad (29)$$

where

DM_{rough}	annual intake of DM with roughage (kg cow^{-1} a^{-1} DM)
$DM_{\text{rough ,house}}$	annual intake of DM with roughage consumed indoors (kg cow^{-1} a^{-1} DM)
$DM_{\text{rough ,graz}}$	annual intake of DM with roughage during grazing (kg cow^{-1} a^{-1} DM)
t_{house}	time spent indoors (a a^{-1})
t_{graz}	time spent grazing (a a^{-1})

hence

$$DM_{\text{rough, graz}} = DM_{\text{rough}} \cdot \frac{t_{\text{graz}}}{t_{\text{house}} + t_{\text{graz}}} \qquad (30)$$

Note that the time spent indoors excludes the time needed for milking. Grazing influences the mean NEL content of roughage needed in Equation (13) and the subsequent discussion.

3.4 Gross energy intake and methane emissions from enteric fermentation

In the IPCC methodology, the amount of CH_4 originating from enteric fermentation is a function of gross energy intake (GE).

3.4.1 Gross energy inputs

If the GE contents of the diet components are known, GE can be determined from the respective amounts of the constituents and their GE contents:

$$GE = \sum_{i=1}^{n} m_i \cdot X_{\text{GE,i}} \qquad (31)$$

where

GE	gross energy intake (MJ cow^{-1} a^{-1} GE)
m_i	amount of feed taken in with component i (kg a^{-1})

$X_{GE, i}$ GE content of feed component i (MJ kg^{-1} GE)

3.4.2 Methane conversion factor

The CH_4 emission from enteric fermentation is derived from the gross energy intake and the methane conversion factor as follows:

$$EF_{CH4, ent} = GE \cdot \frac{x_{CH4} \cdot \alpha}{\eta_{CH4}} \quad (32)$$

where

- $EF_{CH4, ent}$ emission factor for CH_4 from enteric fermentation (kg cow^{-1} a^{-1} CH_4)
- GE gross energy intake (MJ cow^{-1} d^{-1})
- x_{CH4} methane conversion factor (MJ MJ^{-1})
- α time units conversion factor (α = 365 d a^{-1})
- η_{CH4} energy content of methane (η_{CH4} = 55.65 MJ (kg CH_4)$^{-1}$)

Ellis et al. (2007) investigated 10 regression approaches relating $x_{CH4, GE}$ to feed. The equation using entities provided in the German inventory yielding the smallest root mean square prediction error uses the DM intake as in the following equation:

$$x_{CH4,GE} = \frac{E_{CH4}}{GE} = \frac{1}{GE} \cdot \left(a + b \cdot DM\right) \quad (33)$$

where

- $x_{CH4, GE}$ methane conversion factor related to GE (MJ MJ^{-1})
- E_{CH4} methane emitted daily (MJ cow^{-1} d^{-1})
- GE gross energy intake (MJ cow^{-1} d^{-1})
- a constant (a = 3.23 MJ cow^{-1} d^{-1})
- b coefficient (b = 0.809 MJ MJ^{-1})
- DM DM intake (kg cow^{-1} d^{-1})

Equation (33) is used in CDC09.

4 Nitrogen intake and excretion

4.1 Nitrogen intake

The N intake can be calculated using the following equation:

$$m_{feed} = x_N \cdot \sum_{1}^{i} DM_i \cdot x_{N, XP, i} \quad (34)$$

where

- m_{feed} amount of nitrogen in feed (kg cow^{-1} a^{-1} N)
- x_N nitrogen content of crude protein (x_N = 1/6.25 kg kg^{-1} N)
- DM_i amount of DM consumed with feed constituent i (kg cow^{-1} a^{-1} ME)
- $x_{N, XP, i}$ crude protein content of feed constituent i (kg kg^{-1} XP)

A feed constituent can either be fed in animal housing or consumed by grazing.

However, the applicability of this equation is restricted to those cases where both the amounts fed and the diet composition are known. For emission inventories, the amount of DM intake can be modelled adequately. For the protein content of the feed assumptions have to be made with regard to typical regional feeds.

4.2 Nitrogen excretion rates

The accuracy of the modelling of the emission of N species depends significantly on the accuracy of the assessment of N excretion rates (Webb et al., 2005). Both overall and renal excretion rates are needed (Dämmgen and Hutchings, 2008).

4.2.1 Total nitrogen excretion

The nitrogen balance offers a direct assessment of the amount of N excreted:

$$\begin{aligned} m_{excr} &= m_{faeces} + m_{urine} \\ &= m_{feed} - \left(m_l + m_g + m_p + m_s\right) \end{aligned} \quad (35)$$

where

- m_{excr} amount of N excreted in faeces and urine (kg cow^{-1} a^{-1} N)
- m_{faeces} amount of N excreted in faeces (kg cow^{-1} a^{-1} N)
- m_{urine} amount of N excreted in urine (kg cow^{-1} a^{-1} N)
- m_{feed} amount of N taken in in feed (kg cow^{-1} a^{-1} N)
- m_l amount of N exported in milk (kg cow^{-1} a^{-1} N)
- m_g amount of N retained in weight gained (kg cow^{-1} a^{-1} N)
- m_p amount of N excreted in conception products (kg cow^{-1} a^{-1} N)
- m_s amount of N lost in skin and hair (kg cow^{-1} a^{-1} N)

4.2.2 Composition of excreted nitrogen

Emissions of N species are usually related to the reactive nitrogen excreted. This is almost entirely excreted with urine and consists of urea and allanthoin (see e.g. Dämmgen and Erisman, 2005). As the enzyme urease is ubiquitous, these compounds decompose readily to yield ammonium (NH_4). NH_4 and NH_3 in excreta are summarized as total ammoniacal nitrogen (TAN).

It would be advantageous to assess renal N excretion directly. However, no simple modelling procedure is available. Complex models such as DAFOSYM (Rotz et al., 1992), the INRA model (Martin and Sauvant, 2007) or Molly (e.g. Johnson and Baldwin, 2008) require input information that is not normally available. Renal N excretion cannot be related to the N intake with feed satisfactorily (e.g. Rohr, 1992; Kebreab et al., 2001, 2002; Gehman et al., 2008). For the purpose of inventory making, measurements of milk urea N are likely to provide an adequate tool to estimate renal N excretion (e.g. Lebzien et al., 2008). These data is not available yet, so an indirect approach of quantifying faecal N excretion is used:

$$m_{\text{urine}} = m_{\text{excr}} - m_{\text{faeces}} \qquad (36)$$

where

m_{urine}	amount of N excreted in urine (kg cow^{-1} a^{-1} N)
m_{excr}	amount of N excreted in faeces und urine (kg cow^{-1} a^{-1} N)
m_{faeces}	amount of N excreted in faeces (kg cow^{-1} a^{-1} N)

Faecal N excretion is almost independent of the N intake with feed. It is rather dominated by microbial XP synthesis in the rumen. The calculation procedure used in DIAS and CDC09 (Equation (37), is based on Danish experimental results, and takes N input into account. However, the effect of N in feed is comparatively small:

$$m_{\text{faeces}} = \alpha \cdot \beta \cdot \left(a \cdot \frac{m_{\text{feed}}}{\alpha} + \left(b \cdot \frac{DM}{\alpha} + c \cdot \left(\frac{DM}{\alpha} \right)^2 \right) \cdot x_{\text{N}} \right) \qquad (37)$$

where

m_{faeces}	N excreted in faeces (kg cow^{-1} a^{-1} N)
α	time units conversion factor (α = 365 d a^{-1})
β	mass units conversion factor (β = 0.001 kg g^{-1})
m_{feed}	N intake in feed (kg cow^{-1} a^{-1} N)
a	constant (a = 0.04 g kg^{-1})
DM	DM intake (kg cow^{-1} a^{-1})
b	constant (b = 20 g kg^{-1})
c	constant (c = 1.8 g kg^{-2} cow d)
x_{N}	nitrogen content of crude protein (x_{N} = 1/6.25 kg kg^{-1} N)

The TAN content of excreta X_{TAN} is then calculated as percentage related to the total amount of N excreted.

$$X_{\text{TAN}} = \frac{m_{\text{urine}}}{m_{\text{excr}}} \qquad (38)$$

4.2.3 *Nitrogen intake with feed*

CDC09 calculates the N intake with feed as follows:

$$m_{\text{feed}} = \left(dm_{\text{rough}} \cdot X_{\text{XP, rough}} + dm_{\text{conc}} \cdot X_{\text{XP, conc}} \right) \cdot x_{\text{N}} \qquad (39)$$

where

m_{feed}	amount of N intake in feed (kg cow^{-1} a^{-1} N)
dm_{rough}	DM intake with roughage (kg cow^{-1} a^{-1} DM)
$X_{\text{XP, rough}}$	mean XP content of roughage (kg kg^{-1} XP)
dm_{conc}	DM intake with concentrates (kg cow^{-1} a^{-1} DM)
$X_{\text{XP, conc}}$	mean XP content of concentrates (kg kg^{-1} XP)
x_{N}	N content of XP (x_{N} = 1/6.25 kg kg^{-1} N)

4.2.4 *Nitrogen exported in milk*

In CDC09, m_{l} is related to milk yield and milk protein content

$$m_{\text{l}} = Y_{\text{m}} \cdot X_{\text{MP, milk}} \cdot x_{\text{N, milk}} \qquad (40)$$

where

m_{l}	amount of N exported in milk (kg cow^{-1} a^{-1} N)
Y_{m}	annual milk yield (kg cow^{-1} a^{-1})
$X_{\text{MP, milk}}$	protein content of milk (kg kg^{-1} MP)
$x_{\text{N, milk}}$	N content of milk protein ($x_{\text{N, milk}}$ = 1/6.38 kg kg^{-1} N)

4.2.5 *Nitrogen in weight gain and conception products*

A similar approach is used to quantify m_{g} and m_{p}:

$$m_{\text{g}} = \Delta w \cdot x_{\text{N, cow}} \qquad (41)$$

where

m_{g}	amount of N retained in weight gained (kg cow^{-1} a^{-1} N)
Δw	weight gain (kg cow^{-1} a^{-1})
$x_{\text{N, cow}}$	mean N content of whole cow body ($x_{\text{N, cow}}$ = 0.0256 kg kg^{-1} N) (DLG, 2005)

$$m_p = n \cdot w_{calf} \cdot x_{N, calf} \quad (42)$$

where

m_p	amount of N retained in conception product (kg cow^{-1} a^{-1} N)
n	number of calves per cow and year
w_{calf}	weight of calf (kg calf^{-1})
$x_{N, cow}$	mean N content of whole calf body ($x_{N, calf}$ = 0.0296 kg kg^{-1} N) (DLG, 2005)

4.2.6 Nitrogen in skin and hair

The amount of N lost in hair and skin can be obtained from a simple approach:

$$m_s = \alpha \cdot \beta \cdot d \cdot \left(\frac{w}{w_{unit}} \right)^e \quad (43)$$

where

m_s	N losses in skin and hair N (kg cow^{-1} a^{-1} N)
α	time units conversion factor (α = 365 d a^{-1})
β	mass units conversion factor (β = 0.001 kg g^{-1})
d	coefficient (d = 0.018 g cow^{-1} d^{-1} N)
w	animal weight (kg cow^{-1})
w_{unit}	animal weight unit (w_{unit} = 1 kg cow^{-1})
e	exponent (e = 0.75)

4.2.7 Nitrogen entering pasture and the manure management system

The overall amount of nitrogen considered for the assessment of the pasture and manure management mass flow is:

$$m_{MM} = m_{faeces} + m_{urine} + m_s \quad (44)$$

where

m_{MM}	amount of N entering pasture and the manure management system (kg cow^{-1} a^{-1} N)
m_{faeces}	amount of N excreted with faeces (kg cow^{-1} a^{-1} N)
m_{urine}	amount of N excreted with urine (kg cow^{-1} a^{-1} N)
m_s	amount of N lost in skin and hair (kg cow^{-1} a^{-1} N)

The amounts of organic N, $m_{org, MM}$, and TAN_{MM} are:

$$m_{org, MM} = m_{faeces} + m_s \quad (45)$$

$$TAN_{MM} = m_{urine} \quad (46)$$

5 Excretion of volatile solids (VS)

In its Tier 2 approach, IPCC (2006), pg. 10.42, relates the emissions of CH_4 from manure management to the rate of volatile solids excreted. The equation may be re-written as follows:

$$VS_{excr} = \frac{1}{b} \cdot (FE + UE) \cdot (1 - X_{ash}) \quad (47)$$

where

VS_{excr}	amount of VS excreted daily (kg cow^{-1} d^{-1} VS)
b	conversion factor for dietary GE per kg of DM (b = 18.45 MJ kg^{-1})
FE	faecal energy excreted (MJ cow^{-1} d^{-1})
UE	urine energy excreted (MJ cow^{-1} d^{-1})
X_{ash}	ash content of faeces (kg kg^{-1})

IPCC (2006), vol. 3, pg. 4.23, explains b as being "the energy density of feed is about 18.45 MJ per kg of DM. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock."

The **faecal energy** can be expressed as

$$FE = GE \cdot (1 - X_{DE}) \quad (48)$$

where

GE	gross energy intake (MJ cow^{-1} d^{-1})
X_{DE}	digestibility of organic matter (kg kg^{-1})

For simplicity, X_{DE} is taken to be constant for a given diet, even though in reality, it will vary between breeds and physiological states.

The **urine energy** is related to the gross energy

$$UE = a \cdot GE \quad (49)$$

where a is generally assumed to be a more or less constant proportion 0.03 < a < 0.07. IPCC (2006), pg. 10.42, suggests

a	constant (a = 0.04 MJ MJ^{-1})

The **ash content** X_{ash} varies with time and feed. For the purpose of emission reporting, IPCC (2006) suggests a constant ash content of 0.08 kg kg^{-1}. In CDC09 an ash content (national value) of 0.133 kg kg^{-1} as proposed in Hennig and Poppe (1975), pp 172, is used.

In principle, CH_4 emissions from manure management are related to the amount of **degradable volatile solids**. The relation between the excretion rates of total VS (VS_{excr}), degradable VS (VS_d) and non-degradable VS (VS_{nd}) is as follows:

$$VS_{excr} = VS_d + VS_{nd} \qquad (50)$$

In a first approach, VS_d is proportional to VS_{excr}. The factor relating the two is depending on the composition of the excreta. The methodology proposed by IPCC (2006), pg. 10.41, considers this in a "maximum methane producing capacity for manure", B_0, which is listed for each animal category. IPCC (2000), pg. 4.32, recommends that countries should establish national B_0 values. So far, CDC09 relies on the IPCC default value listed in IPCC (2006), Tables 10A-4.

6 Comparison between results obtained with CDC09 and the IPCC (2006) methodologies and the application of the DLG (2005) dataset

It is obvious that the results achieved with the CDC09 approach are likely to differ from those obtained with the IPCC methodology. The different approaches are described and the respective results compared (Chapter 6.1).

It is also important to investigate to what extent modelling of the excretion of animals fed according to requirements deviates from empirical data. Hence, the modelled data are compared to a data set provided in DLG (2005). This data set describes feed intake and N excretion as a function of energy corrected milk (ECM) yield (6000, 8000 and 10000 kg cow^{-1} a^{-1} ECM) and feed composition. For each feeding regime, feed composition varies with performance. (Chapter 6.2)

6.1 Comparison with IPCC

CDC09 was compared with IPCC (2006) for a standard German dairy cow for a range of milk yields and for two contrasting diets using typical milk fat and protein contents.

The national data used for the comparison was obtained partly from the literature. In some cases, it had to be derived from national data sets (e.g. duration of the lactation period). In other cases, assumptions have to be made (e.g. (e.g. weight gain and duration of dry period).

6.1.1 Data set used for comparison

6.1.1.1 Animal performance data

The comparison makes use of the following performance and feed data:

- mean animal weight: 630 kg cow^{-1}, weight gain 80 kg cow^{-1} in 3 a;
- milk fat content 40 g kg^{-1}, milk protein content 34 g kg^{-1}

Milk yields between 4500 and 10000 kg cow^{-1} a^{-1} are taken into consideration.

6.1.1.2 Diets

The exemplary calculations made for this paper differentiate between two common diets. Diet 1 is based on a mix of maize and grass silages combined with barley straw and high protein concentrates (Table 1). Diet 2 reflects the situation in the northwest German grassland region and is based on grass silage and straw combined with protein poor concentrates (Table 2). The feed properties are listed in Table 3.

Table 1:
Composition of diet 1 ("mixed") used for intercomparison

Feed components	Share
Roughage	kg kg^{-1} DM
grass silage	0.46
maize silage	0.46
barley straw	0.08
Concentrates	kg kg^{-1} DM
standard concentrates MLF 18/3	1.00

Table 2:
Composition of diet 2 ("grass") used for intercomparison

Feed components	Share
Roughage	kg kg^{-1} DM
grass silage	0.97
barley straw	0.03
Concentrates	kg kg^{-1} DM
barley	0.88
sugar beet shreds	0.12

Table 3:

Standard data used to establish the comparison data

Feed constituent	DM content	ME in DM	NEL in DM	DE in DM	GE in DM	XP in DM
	kg kg^{-1}	MJ kg^{-1}	MJ kg^{-1}	MJ kg^{-1}	MJ kg^{-1}	kg kg^{-1}
grass (pasture)	0.19	10.6	6.35	14.1	18.45	0.19
grass silage	0.35	10.2	6.15	12.55	17.94	0.16
grass silage DLG 1	0.35	10.2	6.0	12.9	18.2	0.16
grass silage DLG 2	0.35	10.4	6.3	13.4	18.5	0.16
maize silage	0.27	10.95	6.6	12.45	18.00	0.08
maize silage DLG 1	0.27	10.8	6.5	13.4	18.5	0.08
maize silage DLG 2	0.27	11.0	6.7	13.7	18.5	0.08
straw (barley)	0.86	6.4	3.5	8,62	18.20	0.04
barley (grain)	0.88	12.9	8.2	15.5	18.6	0.119
wheat (grain)	0.88	11.6	7.5	16.36	18.52	0.121
rape seed expeller	0.90	12.5	7.5	15.2	20.3	0.396
soya expeller	0.91	12.1	7.6	16.2	22.5	0.440
sugar beet shreds	0.90	11.9	7.4	13.8	18.2	0.099
concentrate MLF 18/3	0.88	10.8	6.7	15.57	18.86	0.180

6.1.1.3 Annual durations of the lactation and dry periods

The calculation procedures make use of annual milk yields and annual energy requirements which are related to the durations of the lactation and dry periods per year. These data are obtained from the respective absolute durations as shares of the year:

$$t_{\text{lact}} = \frac{t^*_{\text{lact}}}{t^*_{\text{lact}} + t^*_{\text{dry}}} \cdot \alpha \quad (51)$$

$$t_{\text{dry}} = \frac{t^*_{\text{dry}}}{t^*_{\text{lact}} + t^*_{\text{dry}}} \cdot \alpha \quad (52)$$

where

t_{lact} duration of the lactation period (d a^{-1})
$t_{\text{lact}}*$ absolute duration of the lactation period (d)
$t_{\text{dry}}*$ absolute duration of the dry period (d)
α time units conversion factor (α = 365 d a^{-1})
t_{dry} duration of the dry period (d a^{-1})

The absolute duration of the lactation period is the difference of the absolute durations of the interval between calvings and the dry period. The duration between calvings can be treated as a function of the annual milk yield (see e.g. Ferguson, 1996; Seeland and Henze, 2003; and literature cited therein). The German statistical data available illustrate the trend (Figure 2), from which Equation (53) is derived:

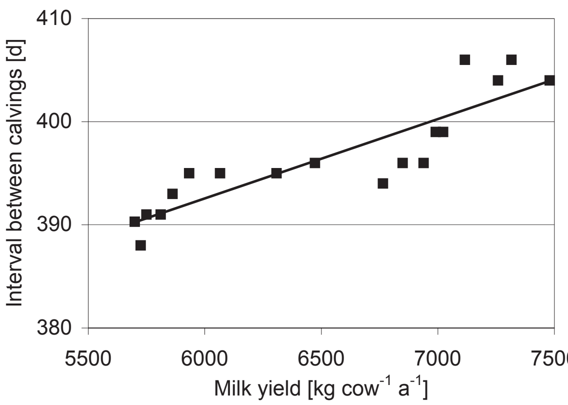

Figure 2:

Relation between mean intervals between calvings (data extracted from ADR 1992 ff) and mean annual milk yield (all herdbook cows). R^2 = 0.74

$$t^*_{\text{lact}} = t^*_{\text{ibc}} - t^*_{\text{dry}} = (a + b \cdot Y_{\text{M}}) - t^*_{\text{dry}} \quad (53)$$

where

$t_{\text{lact}}*$ absolute duration of the lactation period (d)
$t_{\text{ibc}}*$ absolute duration of interval between calvings (d)
$t_{\text{dry}}*$ absolute duration of the dry period (d)
a constant (a = 346.4 d)
b coefficient (b = 0.00769 d kg^{-1} cow a)
Y_{M} annual milk yield (kg cow^{-1} a^{-1}) as reported in official statistics

Values for a and b were obtained for the regression line in Figure 2.

Durations of the dry period normally range from 40 d to 60 d. High performance cows are likely not to conceive as easily as medium performance cows. However, no relation could yet be established to relate this parameter to animal performance. The actual duration of the dry period t_{dry}*is assumed here to be 42 d (reflecting the data provided in GfE, 2001, pg. 23). The annual duration of the dry period t_{dry} is calculated as in Equation (52).

6.1.2 Comparison of energies

6.1.2.1 Energy requirements for maintenance

A direct comparison between CDC09 and IPCC or DIAS is impossible as the units used are not compatible.

6.1.2.2 Total energy requirements

The IPCC methodology is based on NE intakes throughout. If the feeding occurs according to the energy requirements, the amount of net energy required (NE_{tot}) has to equal the net energy intake with feed (NE_{feed}).

$$NE_{feed} = NE_{tot} \tag{54}$$

$$NE_{tot} = \alpha \cdot \left(ne_m + ne_f + ne_{lc} + ne_d + ne_p + ne_g\right) \tag{55}$$

where

- NE_{tot} net energy required (MJ cow^{-1} a^{-1} NE)
- α time units conversion factor (α = 365 d a^{-1})
- ne_m net energy required for maintenance (MJ cow^{-1} d^{-1} NE)
- ne_f net energy needed to obtain food (MJ cow^{-1} d^{-1} NE)
- ne_{lc} net energy for lactation (MJ cow^{-1} d^{-1} NE)
- ne_d net energy required for draft power (MJ cow^{-1} d^{-1} NE)
- ne_p net energy required for pregnancy (MJ cow^{-1} d^{-1} NE)
- ne_g net energy consumed for growth (MJ cow^{-1} d^{-1} NE)

6.1.2.3 Net energy for maintenance

In principle, IPCC (2006), pg. 10.15, uses the same approach as GfE (2001) to quantify NE_m:

$$ne_{m, IPCC} = a_{IPCC} \cdot w_{unit} \cdot \left(\frac{w}{w_{unit}}\right)^{0.75} \tag{56}$$

where

- ne_m net energy required for maintenance (MJ cow^{-1} d^{-1} ME)
- a_{IPCC} constant (b_{IPCC} = 0.386 MJ kg^{-1} d^{-1} ME)
- w_{unit} animal weight unit (w_{unit} = 1 kg cow^{-1})
- w animal weight (kg cow^{-1})

However, the coefficients vary. The GfE methodology results in an ne_m that is about 25 % lower than the results obtained with the IPCC approach. The application of the coefficient a_{CDC09} (see Chapter 3.2.1) leads to values larger than predicted by IPCC (2006).

6.1.2.4 Net energy to obtain feed

As the IPCC (2006) approach (see Equation (3)) is used in the CDC09 methodology as well, no differences occur.

6.1.2.5 Net energy for lactation

The only net energy entity that can be compared between the CDC09 (i.e. GfE) and IPCC (2006) methodologies is the net energy for lactation.

IPCC (2006), pg. 10.18, relates the energy used for lactation to milk yield and milk fat contents:

$$ne_{l, IPCC} = y_m \cdot \left(c_{lact\,1, IPCC} + c_{lact\,2, IPCC} \cdot x_{fat}\right) \tag{57}$$

where

- $ne_{l, IPCC}$ net energy for lactation (MJ cow^{-1} d^{-1} NE)
- y_m milk yield (kg cow^{-1} d^{-1})
- $c_{lact\,1, IPCC}$ constant ($c_{lact\,1, IPCC}$ = 1.47 MJ kg^{-1})
- $c_{lact\,2, IPCC}$ coefficient ($c_{lact\,2, IPCC}$ = 40 MJ kg^{-1})
- x_{fat} mass fraction of fat (kg kg^{-1})

In principle, the results obtained from both approaches are similar (Figure 3). The national approach yields larger energy requirements. Differences between the two procedures are increasing with time.

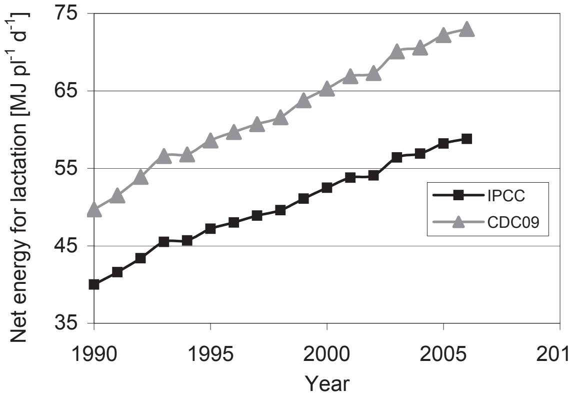

Figure 3:

Time series of the net energy requirements for lactation as calculated using the IPCC (2006) and the CDC09 methodologies

However, CDC09 allows to investigate the option of modified fat and increased protein contents on trace gas emissions (e.g. Brade et al., 2008).

6.1.2.6 Net energy for pregnancy

The IPCC methodology recommends to calculate the net energy for pregnancy proportional to the maintenance energy (IPCC, 2006, pg. 10.20).

$$ne_{\text{p, IPCC}} = c_{\text{preg}} \cdot ne_{\text{m}} \tag{58}$$

where

$ne_{\text{p, IPCC}}$ net energy required for pregnancy (MJ cow^{-1} d^{-1})
c_{preg} coefficient for pregnancy (c_{preg} = 0.10; IPCC(2006)-10.20, Table 10.7)
ne_{m} net energy required for maintenance (MJ cow^{-1} d^{-1})

The IPCC and the CDC09 methodologies differ in principle, as they relate the energy requirements for pregnancy to different entities. The results obtained are quite different (see Figure 4). This is because with increasing mean live weights of cows in Germany, the IPCC methodology suggests increasing energy requirements for pregnancy. However, in the CDC09 method, the simultaneously increasing intervals between calvings indicate a decrease in energy requirements per cow and year.

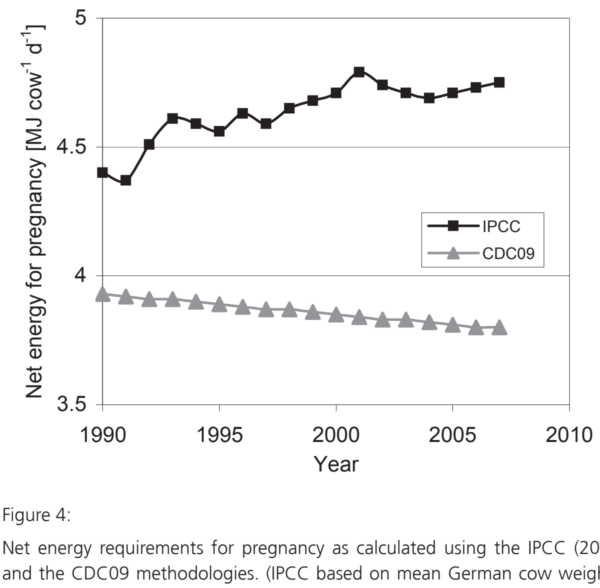

Figure 4:

Net energy requirements for pregnancy as calculated using the IPCC (2006) and the CDC09 methodologies. (IPCC based on mean German cow weights; CDC09 relying on numbers of births per cow and year)

The time series of calf weights used by ADR (1992 to 2007) differentiates between various breeds, but does not exhibit any changes between 1992 and 2007.

Neither IPCC (2006) nor CDC09 relate $NE_{\text{p, IPCC}}$ or $NEL_{\text{p, Ger}}$ to a calf weight. IPCC (2006) does not consider the number of births per year; it also fails to give a reference cow weight, for which the relation was designed.

6.1.2.7 Net energy for growth

The IPCC methodology relates the net energy for growth to a modified metabolic weight and the weight gained (IPCC(2006)-10.17):

$$ne_{\text{g, IPCC}} = a \cdot w_{\text{unit}} \cdot \left(\frac{w}{b \cdot w_{\text{unit}}} \right)^{\text{c}} \cdot \left(\frac{\Delta w}{\alpha \cdot w_{\text{unit}}} \right)^{\text{d}} \tag{59}$$

where

$ne_{\text{g, IPCC}}$ NE required for growth (MJ cow^{-1} d^{-1} NE)
a constant (a = 22.02 MJ kg^{-1} NE)
w mean animal weight of the population ($a$kg cow^{-1})
b constant (b = 0.8)
w_{unit} animal weight unit (w_{unit} = 1 kg cow^{-1})
c exponent (c = 0.75)
Δw weight gain (kg cow^{-1} a^{-1})
α time units conversion factor (α = 365 d a^{-1})
d exponent (d = 1.097)

The explanations given in IPCC (2006), pg. 10.17 suggest that this procedure is to be applied to growing animals rather than to dairy cattle with a moderate weight gain rate.

Thus, CDC09 uses the GfE (2001) approach instead as described in Equation (8).

6.1.3 Dry matter intake and related entities

CDC09 relates the intakes of GE, DE, ME, ash and nitrogen to the amount of DM taken in with the feed components using the following equations:

$$GE = \sum_{\text{i=1}}^{\text{n}} DM_{\text{i}} \cdot X_{\text{GE, i}} \tag{60}$$

$$DE = \sum_{\text{i=1}}^{\text{n}} DM_{\text{i}} \cdot X_{\text{DE, i}} \tag{61}$$

$$ME = \sum_{\text{i=1}}^{\text{n}} DM_{\text{i}} \cdot X_{\text{ME, i}} \tag{62}$$

$$m_{\text{feed}} = \sum_{\text{i=1}}^{\text{n}} DM_{\text{i}} \cdot X_{\text{XP, i}} \cdot X_{\text{N}} \tag{63}$$

where

GE	gross energy intake (MJ cow^{-1} a^{-1} GE)
DM_i	amount of DM taken in with component i (kg a^{-1})
$X_{GE, i}$	GE content of feed component i (MJ kg^{-1} GE)
$X_{DE, i}$	DE content of feed component i (MJ kg^{-1} DE)
$X_{ME, i}$	ME content of feed component i (MJ kg^{-1} ME)
m_{feed}	amount of nitrogen intake (kg cow^{-1} a^{-1} N)
$X_{XP, i}$	crude protein content of feed component i (kg kg^{-1} XP)
X_N	nitrogen content of crude protein (X_N = 1/6.25 kg kg^{-1} N)

The IPCC (2006) methodology does not provide an approach to calculate DM intakes for the high quality forages used in Germany (IPCC, 2006, pg. 10.22). Thus, a direct comparison is impossible.

6.1.4 Total gross energy requirements

According to IPCC (2006), pg 10.21, GE is assessed as follows:

$$ge_{IPCC} = \left(\frac{ne_m + ne_f + ne_{lc} + ne_d + ne_p}{\left\{\frac{ne}{de}\right\}} + \frac{ne_g}{\left\{\frac{ne_g}{de}\right\}} \right) \cdot \frac{1}{X_{DE}} \qquad (64)$$

where

ge_{IPCC}	gross energy intake (MJ cow^{-1} d^{-1} GE)
ne_m	net energy required for maintenance (MJ cow^{-1} d^{-1})
ne_f	net energy needed to obtain food (MJ cow^{-1} d^{-1} NE)
ne_{lc}	net energy for lactation (MJ cow^{-1} d^{-1})
ne_d	net energy required for draft power (MJ cow^{-1} d^{-1} NE)
ne_p	net energy required for pregnancy (MJ cow^{-1} d^{-1} NE)
ne	net energy consumed for maintenance, lactation, work and pregnancy (MJ cow^{-1} d^{-1} NE)
de	digestible energy (MJ cow^{-1} d^{-1} DE)
ne_g	net energy consumed for growth (MJ cow^{-1} d^{-1} NE)
X_{DE}	mean digestible energy as fraction of gross energy (MJ MJ^{-1})

The fractions in braces ({}) are calculated according to Equations (65) and (66) (IPCC (2006) pg 10.20, eq. 10.14;. IPCC (2006) pg 10.21, eq. 10.15).

$$\left\{\frac{ne}{de}\right\} = 1.123 - 0.4092 \cdot X_{DE} + 0.1125 \cdot X_{DE}^2 - \frac{0.254}{X_{DE}} \qquad (65)$$

where

ne	net energy consumed for maintenance, lactation, work and pregnancy (MJ cow^{-1} d^{-1})
de	digestible energy (MJ cow^{-1} d^{-1})
X_{DE}	digestible energy expressed as fraction of GE (MJ MJ^{-1})

$$\left\{\frac{ne_g}{de}\right\} = 1.164 + 0.516 \cdot X_{DE} + 0.1308 \cdot X_{DE}^2 - \frac{0.374}{X_{DE}} \qquad (66)$$

where

ne_g	net energy required for weight gain (MJ cow^{-1} d^{-1})
de	digestible energy (MJ cow^{-1} d^{-1})
X_{DE}	digestible energy expressed as fraction of GE (MJ MJ^{-1})

As illustrated in Figure 5, CDC09 calculates GE intakes that exceed those modelled in the IPCC approach for milk yields for all milk yields due to increased nel_m and nel_{lc}. The two diets yield very similar amounts of GE.

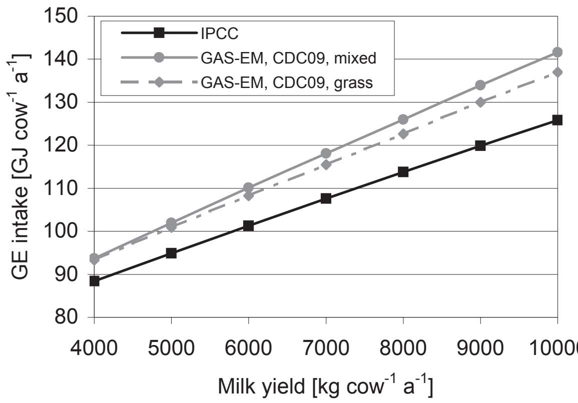

Figure 5:

Gross energy intake as calculated with the IPCC and the CDC09 modules for different annual milk yields

6.1.5 Methane emissions from enteric fermentation

The CH_4 emission from enteric fermentation is derived from the gross energy intake and the methane conversion factor as follows:

$$EF_{CH4,\,ent} = ge \cdot \frac{x_{CH4} \cdot \alpha}{\eta_{CH4}} \quad (67)$$

where

$EF_{CH4,\,ent}$	emission factor for CH_4 from enteric fermentation (kg cow^{-1} a^{-1} CH_4)
ge	gross energy intake (MJ cow^{-1} d^{-1})
x_{CH4}	methane conversion factor (MJ MJ^{-1})
α	time units conversion factor (α = 365 d a^{-1})
η_{CH4}	energy content of methane (η_{CH4} = 55.65 MJ (kg $CH_4)^{-1}$)

Whereas x_{CH4} is a constant in the IPCC approach, it varies with feed composition in CDC09. As shown in Figure 6, methane conversion factors used in CDC09 fall below the IPCC default values. This was also observed in detailed Dutch and US studies (Smink et al., 2005; Kebreab et al., 2008). However, CDC09 methane conversion factors are in the range proposed in IPCC (2006) pg.10.30 for countries with high quality feed.

Conversion factors for mixed and grass based diets are almost identical.

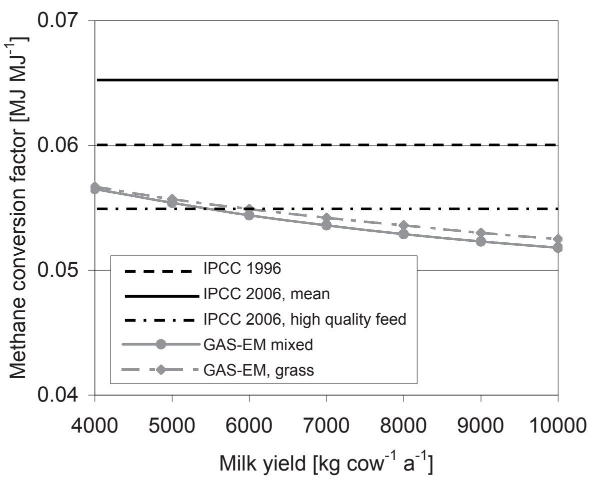

Figure 6:

Methane conversion factors as calculated with the IPCC and the CDC09 modules for different annual milk yields. The CDC09 lines for mixed and grass are almost identical.

As a consequence, the results obtained for CH_4 emission factors for enteric fermentation differ considerably (Figure 7).

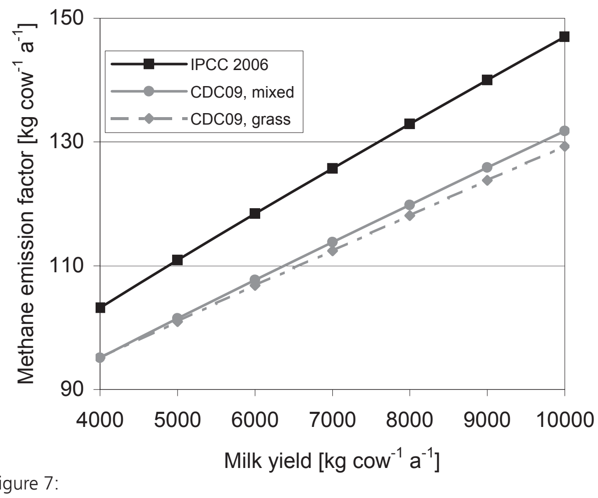

Figure 7:

Methane emission factors as calculated with the IPCC and the CDC09 modules for different annual milk yields. The CDC09 lines for mixed and grass are almost identical.

The difference observed is in the order of magnitude of 10 %. Emission factors of the mixed and grass silage based diets are almost identical.

6.1.6 Excretion of volatile solids

IPCC and the CDC09 approaches are identical in principle. However, CDC09 uses different constants.

As discussed in Chapter 6.1.4, **GE intakes** calculated with the IPCC and CDC09 approaches deviate.

IPCC (2006), pg. 10.14, recommends a value for the **digestibility** X_{DE} in the range of 0.55 to 0.75. Figure 8 illustrates that the feed quality in German diets is close to the upper limit suggested in IPCC (2006).

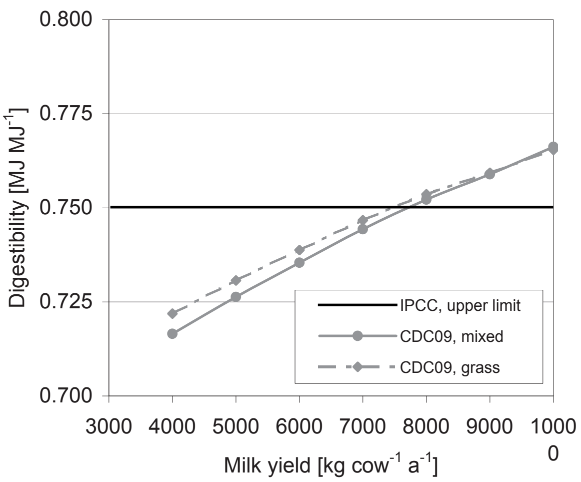

Figure 8:

Mean digestibilities as proposed by IPCC (2006) and as calculated with the CDC09 module for different annual milk yields

In Figure 9, VS excretions rates calculated according to IPCC use a mean digestibility of 0.65 MJ MJ^{-1}.

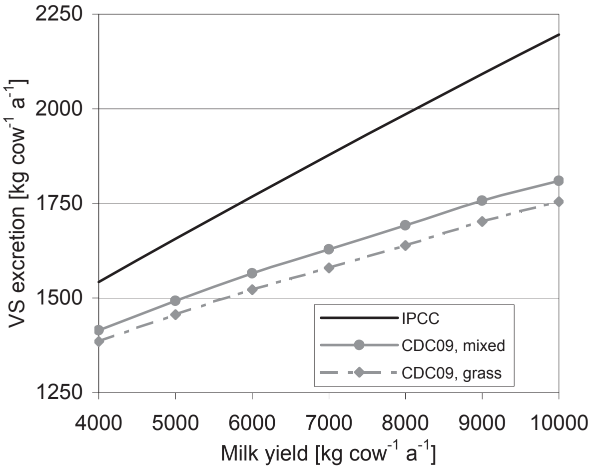

Figure 9:

VS excretion rates as calculated according to IPCC (2006) and the CDC09 module for different annual milk yields

For all milk yields, CDC09 VS excretion rates deviate significantly from IPCC.

In principle, CH_4 emissions from manure management should not be related to VS as in Equation (47), but to its degradable portion (see Sommer et al., 2004). In practice, it is assumed that this fraction is constant. At present there is no proposal to model its amount.

6.2 Comparison with the DLG (2005) dataset

DLG (2005) describes a consistent data set of feed, feed composition, properties of feed constituents and N excretion rates for cows with annual milk yields of 6000, 8000 and 10000 kg cow^{-1} a^{-1} ECM. Animal weight and weight gain are not mentioned. Hence, this comparison assumes a mean weight of 630 kg cow^{-1} and a weight gain of 20 kg cow^{-1} a^{-1}.

The authors of DLG (2005) communicated the feed constituent properties (Obermaier and Spiekers, 2008). They are listed in Table 3. For milk yields of 6000 and 8000 kg cow^{-1} a^{-1} ECM grass silage DLG 1 and maize silage DLG 1 are used, for yields of 10000 kg cow^{-1} a^{-1} ECM grass silage DLG 2 and maize silage DLG 2.

6.2.1 Daily milk yield and energy corrected milk yield

DLG (2005) relates dry matter intake and nitrogen excretion rates to energy corrected daily milk yields.

The daily milk yield is related to the annual duration of the lactation period according to Equation (68):

$$y_{M} = \frac{Y_{M}}{t_{lact}} \qquad (68)$$

where

y_M	daily milk yield, uncorrected (kg cow^{-1} d^{-1} milk)
Y_M	annual milk yield (kg cow^{-1} a^{-1} milk)
t_{lact}	duration of the lactation period (d a^{-1})

Energy corrected milk yield considers the fat and protein contents of the milk as in Equation (69):

$$y_{ECM} = y_{M} \cdot \left(a + b \cdot x_{fat} + c \cdot x_{protein}\right) \qquad (69)$$

where

y_{ECM}	daily milk yield (energy corrected) (kg cow^{-1} d^{-1})
y_M	daily milk yield, uncorrected (kg cow^{-1} d^{-1} milk)
a	constant (a = 0.3246)
b	coefficient (b = 12.86)
x_{fat}	mass fraction of fat (kg kg^{-1})
c	coefficient (c = 7.04)
$x_{protein}$	mass fraction of protein (kg kg^{-1})

6.2.2 Dry matter intake

6.2.2.1 Total dry matter

The IPCC (2006) methodology does not provide an approach to calculate DM intakes for the high quality forages used in Germany (IPCC, 2006, pg. 10.22).

DM intakes as modelled with CDC09 equal those provided by DLG (2005) (Figure 10). However, DLG (2005) report one digit only with their DM inputs, so differences up to 0.2 Mg cow^{-1} a^{-1} may occur.

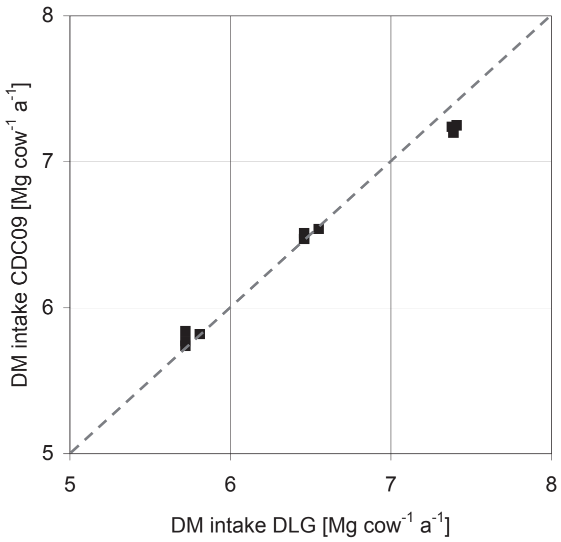

Figure 10:

DM intake for 12 DLG scenarios compared with results of the CDC09 module (broken line: 1 to 1 line)

6.2.2.2 Dry matter with concentrates

The distribution between concentrates and roughage of dry matter intake is decisive for the energy and nitrogen intakes. Figure 11 illustrates that CDC09 and DLG (2005) results deviate slightly, but systematically. Again, as DLG (2005) report one digit only with their DM inputs, differences up to 0.2 Mg cow^{-1} a^{-1} may also apply to concentrates.

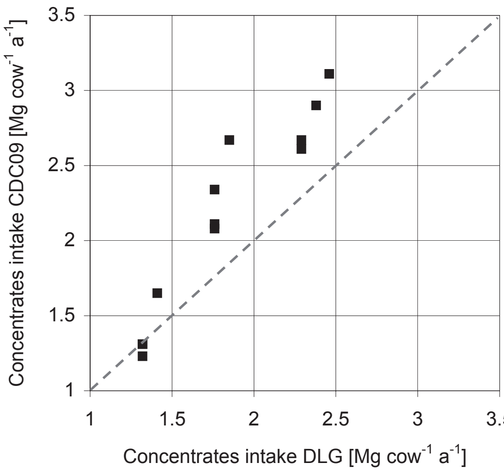

Figure 11:

DM intake with concentrates for 12 DLG scenarios compared with results of the CDC09 module (broken line: 1 to 1 line)

6.2.3 N excretion rates

DLG (2005) provides an independent data set that can be used for a validation of the module. A comparison with CDC09 results is shown in Figure 12. As a whole, CDC09 estimates N excretion rates about 4 % larger than DLG (2005).

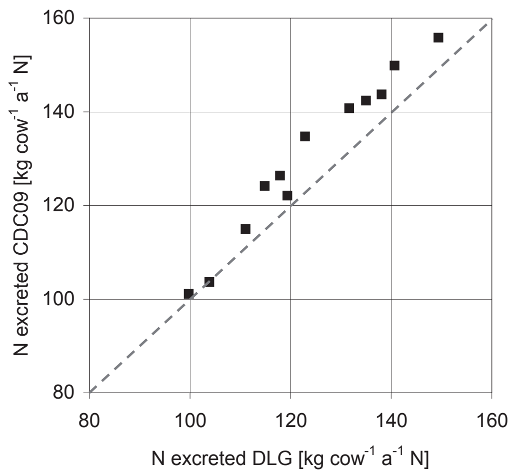

Figure 12:

N excretion rates of 12 DLG scenarios and corresponding results obtained with CDC09

7 Conclusions

The goal to develop a single model from national standard descriptions that allows the assessment of excretions and emissions from a single data set was achieved. The bottom-up CDC09 model agrees well with the top-down DLG calculations based on measurements.

The model can be used to quantify N, TAN and VS excretion as well as CH_4 emissions from enteric fermentation if the amount and composition of feed are known. The model can predict feed intake, if performance data are known adequately. It can thus be a submodel in calculations within a life cycle analysis.

Hence, CDC09 is considered a useful tool for the construction of emission inventories as well as for policy advice.

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