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Modelling excretion rates of German dairy heifers

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Abstract

A model to derive methane emissions from enteric fermentation as well as volatile solids and faecal and renal nitrogen excretions of dairy heifers was developed. It uses start and final weights of the animals, their daily weight gain and the duration of grazing as input parameters.

The model was applied to typical German diet compositions and feed properties. Emissions from enteric fermentation were obtained that exceed those estimated with the IPCC default methodology.

Keywords: *dairy heifers, model, excretion, methane, volatile solids, nitrogen*

Zusammenfassung

Modellierung der Ausscheidungsraten deutscher Aufzuchtrinder

Es wurde ein Modell für Aufzuchtrinder entwickelt, mit dessen Hilfe die Methanemissionen aus der Verdauung sowie die Ausscheidungen von organischer Masse ("volatile solids") und Stickstoff mit Kot und Harn berechnet werden können. Das Modell nutzt Anfangs- und Endmassen der Tiere, die tägliche Zunahme sowie die Dauer des Weidegangs als Eingangsgrößen.

Mit in Deutschland üblichen Futterzusammensetzungen und Futterqualitäten wurden typische Emissionen ermittelt. Die Ergebnisse für Methan aus der Verdauung sind deutlich höher als die mit dem IPCC-default-Verfahren erhaltenen Werte.

Schlüsselwörter: *Aufzuchtrinder, Modell, Ausscheidungen, Methan, organische Masse, Stickstoff*

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1 Introduction

International and national activities aim at a reduction of the emissions of greenhouse gases (GHG) and air pollutants, in particular ammonia (NH_3), from agricultural sources. In this process, a first step is to quantify excretion by livestock, which presupposes the availability of models that depict the emitting processes and their controlling parameters. A second step is to apply them to current practice and identify potential reduction potentials.

In most countries cattle production is the largest source of agricultural emissions. In Germany methane (CH_4) emissions from heifers alone exceed those of all non-cattle animals. For NH_3, the raising of heifers contributes about 8 % to the national total (UBA, 2015). Hence, it is considered worthwhile to establish detailed excretion models for dairy and beef heifers that provide the requirements mentioned above. This work deals with the description of dairy heifers for reproduction only, and fills the "gap" between the calf and the dairy cow models described in Dämmgen et al. (2009; 2013), by:

- quantifying the metabolic energy (ME) requirements,
- calculating the feed intake (amounts, dry matter, nitrogen (N), etc.) and
- deriving the excretion rates of enteric CH_4, volatile solids (VS) as well as faecal and renal N,

and using the variables provided in German statistics (weights, weight gains, grazing times) and German national data for constants wherever possible.

Calculation of VS excretion then allows determination of the emissions of CH_4 from housing, storage and grazing using the information provided in Dämmgen et al. (2011; 2012). Faecal and renal N excretion rates are used to quantify emissions of the relevant N species NH_3, nitric oxide (NO), nitrous oxide (N_2O) and di-nitrogen (N_2) as a function of housing and manure storage types, manure application technologies and intervals before incorporation of manure in accordance with EMEP (2013). For principles of these calculations see Rösemann et al. (2015), Chapter 4.2 (Emission factors for all cattle).

2 The detailed dairy heifer model

2.1 Raising dairy heifers in Germany – a short overview

In principle, dairy heifers differ from female beef cattle with respect to their daily weight gains (female beef about 800 to 1000 g $animal^{-1}$ d^{-1}, dairy heifers 700 to 800 g $animal^{-1}$ d^{-1} (e.g. GfE, 2001; LfL, 2013; 2014; KTBL, 2014) and hence feed requirements and composition. They are fed and kept different from beef heifers, with a protein rich diet to optimize the development of the reproductive organs. It is quite common to graze dairy heifers for at least part of the year.

When they are about 18 to 21 months old they will be covered, and they will give birth to their calves at the age of 27 to 31 months. Age at first calving, weight gains and final weights have changed considerably in the past two and half decades (Figures 1 to 3). A steady decrease can be observed for months at first calving while weight gains increased. Final weights seem to have stabilized after 2005.

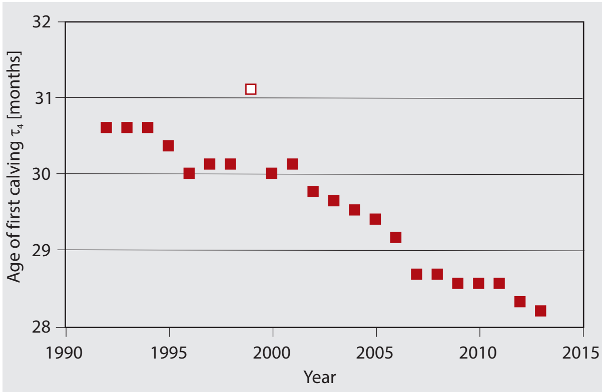

Figure 1
Ages at first calving (τ_4) during the past two decades (national means provided by ADR, 1993 ff, value for 1999 considered as outlier)

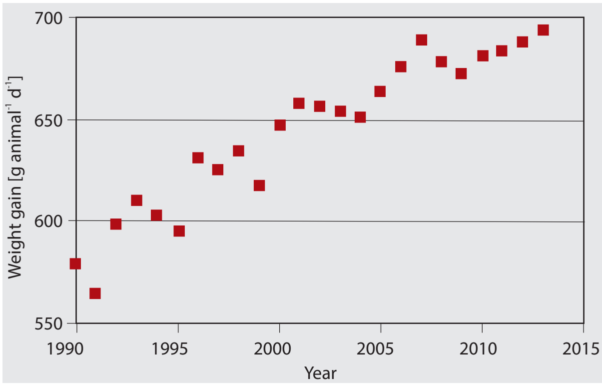

Figure 2
Mean weight gains calculated for German heifers using Equation (1) and official data (see Chapter 3.1)

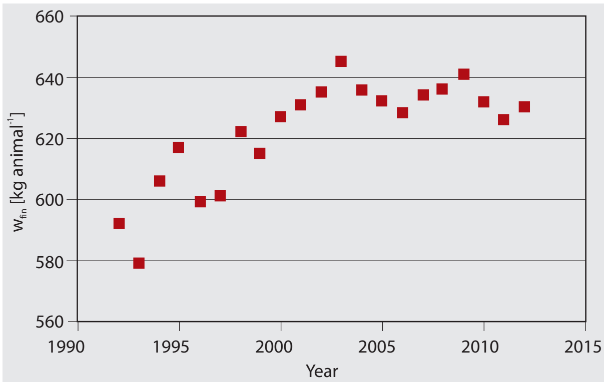

Figure 3
Mean final weights for German heifers (obtained from official data on carcass weights [1])

[1] German statistics provide no information on final live weights of animals. However, carcass weights are listed. As a result of the short productive lifetime of German dairy cows (national average at present is less than 2.8 years; Römer, 2011), almost all female calves have to be used for replacement. Hence we assume that the carcass weights of female cattle older than 1 a provided in the official slaughter statistics apply to dairy heifers. As no other data is available, this weight has to be used to define the transition from heifer to cow. Live weights are derived from carcass weights according to Dämmgen et al. (2010) using the relation $w_4 = a_{carc} + b_{carc} \cdot w_{carc}$, with a_{carc} = 221 kg $animal^{-1}$, b_{carc} = 1,46 kg kg^{-1} and w_{carc} carcass weight (in kg $animal^{-1}$).

German breeders aim at a constant weight gain over the entire period (Figure 4).

As a rule, dairy heifers are grazed part of the time, preferably in the second summer of their lives. Figure 5 shows the mean shares of grazing times for German heifers (including both dairy and beef heifers).

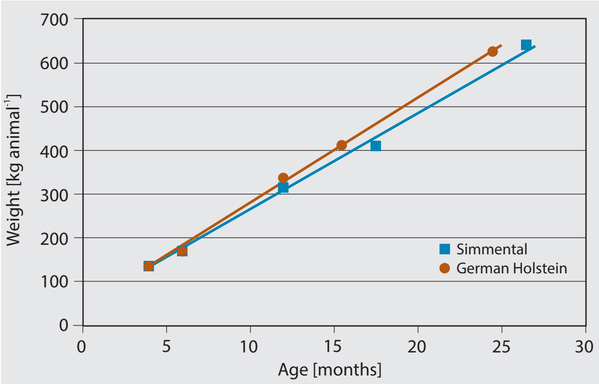

Figure 4
Weights of Simmental and German Holstein heifers as recommended by DLG (2008)

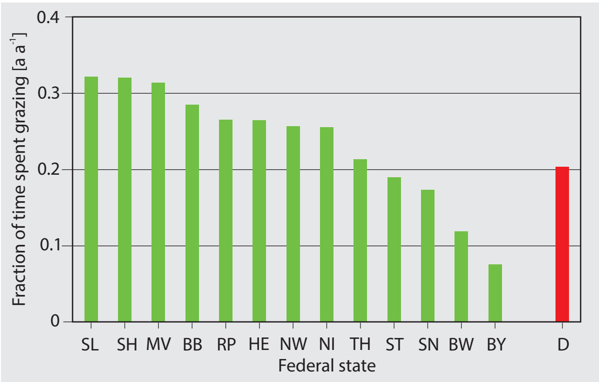

Figure 5
Mean grazing times of heifers for the German federal states and the weighted German mean [2)] in 2010 (Data supplied by Statistisches Bundesamt)

Any model that is to reflect the German situation has to treat final weights, weight gains and grazing times as variables.

2.2 Animal weights, weight gains and feeding phases

As shown in Figure 4, it is reasonable to base the heifer model on the assumption of a constant weight gain:

$$\Delta w = \frac{w_4 - w_1}{\tau_4 - \tau_1} \qquad (1)$$

where
Δw mean daily weight gain (in kg animal^{-1} d^{-1})
w_4 final weight of a heifer (in kg animal^{-1})
w_1 start weight of a heifer (w_1 = 125 kg animal^{-1})
τ_4 end of the period the animal is a heifer (in d)
τ_1 beginning of the period the animal is a heifer (τ_1 = 0 d)

Δw is deduced from statistics. w_1 is the final weight of calves described in Dämmgen et al. (2013), and taken to be constant to reduce the number of variables. This weight is achieved after about 4 months of life when the lifespan of the heifer begins ($\tau_{start} = \tau_1$). w_4 is the variable weight of first calving at the end of the period the animal is a heifer ($\tau_{fin} = \tau_4$). At the time being (see Figure 1) τ_{fin} is about 28 months. Hence, the overall lifespan spent as heifer is about two years.

Feeding of heifers varies depending on the age of the animal. To be able to distinguish different feeding phases it is necessary to define intermediate weights w_i

$$w_i = w_1 + (\tau_i - \tau_1) \cdot \Delta w \qquad (2)$$

where
w_i weight of a heifer at a time τ_i (in kg animal^{-1})
w_1 start weight of a heifer (w_1 = 125 kg animal^{-1})
τ_i intermediate time (in d)
τ_1 beginning of the time as a heifer (τ_1 = 0 d)
Δw mean daily weight gain (in kg animal^{-1} d^{-1})

Figure 6 gives an overview over relevant times, weights, feeding phases as well as durations of grazing periods.

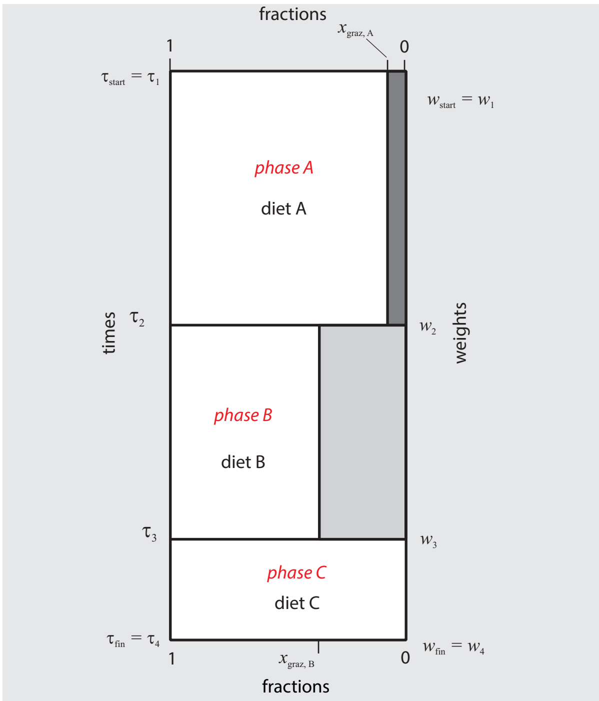

Figure 6
Phases in rearing a heifer – overview over relevant times and weights (shaded areas symbolize grazing, white rectangles housing) (times and weights not to scale)

[2] SL: Saarland; SH: Schleswig-Holstein; MV: Mecklenburg-Western Pomerania; BB: Brandenburg; RP: Rhineland-Palatinate; HE: Hesse; NW: North Rhine-Westphalia; NI: Lower Saxony; TH: Thuringia; ST: Saxony-Anhalt; SN: Saxony; BW: Baden-Württemberg; BY: Bavaria; D: German mean. Weighting takes animal numbers into account.

It is customary to change the composition of the diet when the animals' weight is about 400 to 420 kg animal^{-1} (Weiß et al., 2005; Kirchgeßner et al., 2008; DLG, 2008; Fischer et al., 2011). As can be seen in Figure 4, this is after the first half of the animals' lifespan. In the first half of their time as a heifer (phase A, see Figure 6), their diet (diet A) is richer in energy and protein than in the subsequent phase B (diet B). Towards the end of the pregnancy, the animals require a diet richer in metabolizable energy (ME) and crude protein (CP) contents in order to ensure the foetus is adequately nourished (phase C, diet C).

As phase B requires feed with less ME and CP (diet B), this is the favoured time to graze the animals. As a rule, heifers are grazed at least part of the year in the second half of their time as heifers. Grazing may also occur in phase A. However, grazing may not provide the ME input needed during the final eight weeks before calving (phase C). Here, the animals are housed and fed diet A again, hence diet C = diet A. This allows the rumen microbiome to adjust to the performance requirements of a lactating cow.

From this a *simplified model of feeding phases* is developed using the terms provided in Figure 6.

The duration of phase A is defined by:

$$\Delta t_A = \tau_2 - \tau_1 = x_A \cdot (\tau_4 - \tau_1) \quad (3)$$

with

Δt_A duration of phase A (in d)
τ_2 time at the end of phase A, beginning of phase B (in d)
τ_1 beginning of the period the animal is a heifer, beginning of phase A (in d)
x_A fraction of time spent in phase A (in a a^{-1})
τ_4 end of phase C, end of the period the animal is a heifer (in d)

With the assumptions made above, x_A is half the life span of the heifer ($x_A = \frac{1}{2}$).

The phase model assumes that phase C is taken to last about 2 months, and that the entire period the animal is a heifer is about 24 months. Thus, phase C forms a fraction of one twelfth of the entire period or one sixth of the second year which allows us to define:

$$\Delta t_C = \tau_4 - \tau_3 = x_C \cdot (\tau_4 - \tau_1) = \frac{1}{6}(\tau_4 - \tau_2) \quad (4)$$

and

$$\Delta t_B = \tau_3 - \tau_2 = \frac{5}{6}(\tau_4 - \tau_2) \quad (5)$$

where

Δt_C duration of phase C (in d)
Δt_B duration of phase B (in d)
τ_4 end of phase C, end of the period the animal is a heifer (in d)
τ_3 end of phase B, beginning of phase C (in d)
τ_2 end of phase A, beginning of phase B (in d)

In principle, these fractions apply to the period the animal is a heifer (24 months). Due to lack of information it is used to describe *all* heifers irrespective of the actual period before the animal becomes a lactating dairy cow.

Grazing times have to be treated separately as grazing affects the amounts and the properties of the feed.

The *model concept* (see Figure 6) describes grazing times by defining fractions of the duration of phases A and B dedicated to grazing, $x_{graz, A}$ and $x_{graz, B}$. Grazing occurs preferably in the second year of the period the animal is a heifer, which is reflected in Figure 6 by $x_{graz, B}$ being considerably bigger than $x_{graz, A}$. As mentioned above there is no grazing in phase C.

Official statistics provide time series of grazing times for all heifers including animals raised as beef heifers. However, it is assumed that these time series can be used for dairy heifers, as the share of non-dairy heifers is small in comparison. Unfortunately, the official data do not provide $x_{graz, A}$ and $x_{graz, B}$ but the mean number of days annually spent on pasture that can be converted into an overall mean fraction x_{graz} (see Figure 5). The relation between x_{graz}, $x_{graz, A}$ and $x_{graz, B}$ is

$$x_{graz} = \frac{(\tau_2 - \tau_1) \cdot x_{graz, A} + (\tau_3 - \tau_2) \cdot x_{graz, B}}{\tau_4 - \tau_1} \quad (6)$$

where

x_{graz} fraction of time spent grazing provided by statistics (in a a^{-1})
$x_{graz, A}$ share of time spent grazing in phase A (in a a^{-1})
$x_{graz, B}$ share of time spent grazing in phase B (in a a^{-1})
τ_1 beginning of the period the animal is a heifer, begin of phase A (in d)
τ_2 beginning of phase B, end of phase A (in d)
τ_3 end of phase B, begin of phase C (in d)
τ_4 end of phase C, end of the period the animal is a heifer (in d)

As this is one equation with two unknowns, additional information and assumptions are needed to derive $x_{graz, A}$ and $x_{graz, B}$ from x_{graz}. We use the information that the grazing period for heifers in Germany does not normally exceed half a year and that heifers are grazed preferably in the second year (DLG, 2008; Dawson and Carson, 2005; backed up by expert judgement Martin [3)] and Lange [4)]). As a consequence we assign 0.5 a of grazing to the second year and no grazing to the first year in order to derive a characteristic threshold x^*_{graz} of the mean annual grazing time:

$$x^*_{graz} = \frac{0.5 \text{ a}}{2 \text{ a}} = 0.25 \text{ a a}^{-1} \quad (7)$$

where

x^*_{graz} overall mean of annual grazing time (in a a^{-1})

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As can be seen in Figure 5, there are values of $x_{graz} > x^*_{graz}$ and $x_{graz} \leq x^*_{graz}$. Hence, we assume that $x_{graz} > x^*_{graz}$ is due to additional grazing in the first year of the period the animal is a heifer and that $x_{graz} \leq x^*_{graz}$ means grazing only in the second year. For the latter case, $x_{graz, A} = 0$ and Equation (6) reduces to

$$x_{graz} = \frac{\tau_3 - \tau_2}{\tau_4 - \tau_1} \cdot x_{graz, B} \tag{8a}$$

or, after resolving for $x_{graz, B}$ and taking into account Equation (5),

$$x_{graz, B} = \frac{\tau_4 - \tau_1}{\tau_3 - \tau_2} \cdot x_{graz} = \frac{12}{5} \cdot x_{graz} \tag{8b}$$

where

x_{graz} fraction of time spent grazing provided by statistics (in a a^{-1})
$x_{graz, B}$ share of time spent grazing in phase B (in a a^{-1})
τ_1 begin of the period the animal is a heifer, beginning of phase A (in d)
τ_2 time at the end of phase A, beginning of phase B (in d)
τ_3 end of phase B, beginning of phase C (in d)
τ_4 end of phase C, end of the period the animal is a heifer (in d)

In case of $x_{graz} > x^*_{graz}$ we assign the part of x_{graz} exceeding x^*_{graz} to phase A. This modifies Equation (6) to

$$x_{graz} = \frac{(\tau_2 - \tau_1) \cdot x_{graz, A}}{\tau_4 - \tau_1} + x^*_{graz} \tag{9}$$

or, after resolving for $x_{graz, A}$ and taking into account Equations (3) and (7),

$$x_{graz, A} = 2 \cdot x_{graz} - 0.5 \tag{10}$$

where

$x_{graz, A}$ share of time spent grazing in phase A (in a a^{-1})
x_{graz} fraction of time spent grazing provided by statistics (in a a^{-1})

2.3 Metabolic energy requirements

2.3.1 Determination of cumulative metabolic energy requirements

The determination of ME requirements is the basic tool for feed intake and excretion calculations. As follows from Chapter 2.2, cumulative ME requirements have to be obtained for the various feeding phases. GfE (2001), supplemented by Kirchgeßner et al. (2008), provide daily ME requirements of housed heifers as a function of actual animal weights and animal weight gains (Table 1). This table does not differentiate between genotypes. Weight gains between 0.6 and 0.7 kg animal^{-1} d^{-1} have been common in German animal production (see Figure 2).

Table 1
Metabolic energy requirements of housed heifers (in MJ animal^{-1} d^{-1}) (GfE, 2001, Table 1.5.3; Kirchgeßner et al., 2008), as a function of animal weights and weight gains.

live weight w (kg animal^{-1})	weight gain Δw (kg animal^{-1} d^{-1}) 0.40	0.50	0.60	0.70	0.80	0.90	1.00
150		30.5	32.3	34.1	36.0		
200		37.4	39.6	42.0	44.3	46.6	
250	41.6	43.9	46.7	49.6	52.6	55.8	59.0
300	47.5	50.4	53.6	57.2	60.8	64.6	68.6
350	53.2	56.6	60.5	64.7	69.1	73.7	78.5
400	58.9	62.8	67.3	72.2	77.5	83.2	89.3
450	64.6	69.0	74.2	79.9	86.0	92.7	100.0
500	70.1	75.1	81.0	87.5	94.5	102.0	110.0
550	75.5	81.4	88.0	95.4	103.2	111.6	120.6
600	81.3	87.8	94.9	103.4			

The determination of cumulative ME requirements presuppose the transformation of Table 1 into a steady function and its subsequent integration over time, resulting in Equation (11). For details of its derivation see Appendices 1 and 2.

$$\sum ME_{house, i} = \frac{1}{\Delta w} \cdot \left[a \cdot (w_m - w_n) + \frac{b}{2} \cdot (w_m^2 - w_n^2) \right] \tag{11}$$

where

$\Sigma ME_{house, i}$ cumulative metabolic energy requirements for housed heifers (without grazing) in phase i (in MJ animal^{-1})
Δw daily weight gain (in kg animal^{-1} d^{-1})
a coefficient (in MJ animal^{-1} d^{-1}, see Equation (12))
w_m final weight of heifer in phase i (in kg animal^{-1})
w_n start weight of heifer in phase i (in kg animal^{-1})
b coefficient (in MJ kg^{-1} d^{-1}, see Equation (13))

with phase dependent weights

i	w_m	w_n
A	w_1	w_2
B	w_2	w_3
C	w_3	w_4

and

$$a = \alpha + \beta \cdot \Delta w + \gamma \cdot \Delta w^2 \tag{12}$$

$$b = \delta + \varepsilon \cdot \Delta w + \zeta \cdot \Delta w^2 \tag{13}$$

with

a constant (in MJ animal^{-1} d^{-1})
α constant (α = 4.7665678 MJ animal^{-1} d^{-1})

β coefficient (β = 26.7961752 MJ kg^{-1})
Δw daily weight gain (in kg $animal^{-1}$ d^{-1})
γ coefficient (γ = -24.5867088 MJ animal kg^{-2} d)

b coefficient (MJ kg^{-1} d^{-1}, see Equation (4))
δ constant (δ = 0.097908 MJ kg^{-1} d^{-1})
ε coefficient (ε = 0.0061962 MJ animal kg^{-2} d^{-2})
ζ coefficient (ζ = 0.1020296 MJ $animal^2$ kg^{-3} d)

A comparison of Table 1 and Figure 3 reveals that the data for most final weights in the past two decades have to be obtained from a slight extrapolation, as final weights somewhat exceed 600 kg $animal^{-1}$.

2.3.2 Metabolic energy requirements for single feeding phases and consideration of grazing

Equation (11) has to be applied to each feeding phase and diet, differentiating between housed and grazed animals. The quantification of the cumulative ME requirements for phases A, B and C, ΣME_A, ΣME_B and ΣME_C, has to take into account that grazing animals need extra energy to obtain their feed. As a rule, this so-called energy expenditure is related to the energy requirements for maintenance. It is strongly dependent on the structure of the terrain and the quality of the pasture (e.g. Di Marco and Aello, 1998; Brosh et al., 2006). For dairy heifers, no experimental data are available for Germany. Moreover, the ME requirements are not split up in ME for maintenance, ME_m, and growth, ME_g. Hence estimates have to rely on experimental data for dairy cows, on national estimates or use international default values. Here, the national estimate provided in DLG (2014) and the IPCC (2006) default value for ME_m were used to derive a surcharge factor for gross energy requirements of 10 %, i. e. f_{graz} = 1.1 (for details see Appendix 3). The following equations are used to calculate ME requirements in the three rearing phases of heifers:

$$\sum ME_A = \left[\left(1 - x_{graz,A}\right) + x_{graz,A} \cdot f_{graz}\right] \cdot \frac{1}{\Delta w} \cdot \left[a \cdot \left(w_2 - w_1\right) + \frac{b}{2} \cdot \left(w_2^2 - w_1^2\right)\right] \quad (14)$$

$$\sum ME_B = \left[\left(1 - x_{graz,B}\right) + x_{graz,B} \cdot f_{graz}\right] \cdot \frac{1}{\Delta w} \cdot \left[a \cdot \left(w_3 - w_2\right) + \frac{b}{2} \cdot \left(w_3^2 - w_2^2\right)\right] \quad (15)$$

$$\sum ME_C = \frac{1}{\Delta w} \cdot \left[a \cdot \left(w_4 - w_3\right) + \frac{b}{2} \cdot \left(w_4^2 - w_3^2\right)\right] \quad (16)$$

where
ΣME_A cumulative ME requirements during phase A (in MJ $animal^{-1}$)
$x_{graz,A}$ fraction of time spent grazing in phase A (in a a^{-1})
f_{graz} factor reflecting increased ME requirements during grazing (f_{graz} = 1.1 kg kg^{-1})
Δw daily weight gain (in kg $animal^{-1}$ d^{-1})
a coefficient (in MJ $animal^{-1}$ d^{-1})
w_2 weight of heifer at time τ_2 (in kg $animal^{-1}$)
w_1 start weight of heifer (in kg $animal^{-1}$)
b coefficient (in MJ kg^{-1} d^{-1})
etc.

2.4 Enteric methane emissions

Daily ME requirements allow for the quantification of daily feed intake rates, once the feed properties are known. From the amount of feed constituents taken in, the amounts of CH_4 released from enteric fermentation and the excretion of volatile solids (VS) can be derived.

According to Kirchgessner et al. (1994; 1995), these CH_4 emissions can be obtained from Equation (17). Its applicability for dairy cows was checked in Dämmgen et al. (2012). Equation (17) is then used to derive cumulative emissions (Equation (19)), as M_{CFi}, M_{NFE}, M_{CP} and M_{XF} are linearly related to the daily ME intake,

$$ef_{CH4} = c_{CFi} \cdot M_{CFi} + c_{NFE} \cdot M_{NFE} + c_{CP} \cdot M_{CP} + c_{EE} \cdot M_{EE} + d_{CH4} \quad (17)$$

and

$$EF_{CH4, A} = \frac{\sum ME_A}{\eta_{ME, A}} \cdot \left(c_{CFi} \cdot x_{CFi, A} + c_{NFE} \cdot x_{NFE, A} + c_{CP} \cdot x_{CP, A} + c_{EE} \cdot x_{EE, A}\right) + d_{CH4} \cdot (\tau_2 - \tau_1) \quad (18)$$

where

ef_{CH4} daily CH_4 emission rate (factor) (in kg animal^{-1} d^{-1}) according to Kirchgessner et al. (1994; 1995)
c_{CFi} coefficient (c_{CFi} = 0.079 kg (kg DM)$^{-1}$)
M_{CFi} intake rate of crude fibre (in kg animal^{-1} d^{-1})
c_{NFE} coefficient (c_{NFE} = 0.010 kg (kg DM)$^{-1}$)
M_{NFE} intake rate of N-free extracts (in kg animal^{-1} d^{-1})
c_{CP} coefficient (c_{CP} = 0.026 kg (kg DM)$^{-1}$)
M_{CP} intake rate of crude protein (in kg animal^{-1} d^{-1})
c_{EE} coefficient (c_{EE} = – 0.212 kg (kg DM)$^{-1}$
M_{EE} intake rate of ether extract (crude fat) (in kg animal^{-1} d^{-1})
d_{CH4} constant (d_{CH4} = 0.063 kg animal^{-1} d^{-1})

and

$EF_{CH4, A}$ cumulative enteric CH_4 emissions in phase A (in kg animal^{-1})
ΣME_A cumulative ME requirements in phase A including grazing (in MJ animal^{-1})
$\eta_{ME, A}$ mean ME content of diets A (in MJ (kg DM)$^{-1}$)
$x_{CFi, A}$ mean content of crude fibre in diets A (in kg (kg DM)$^{-1}$)
$x_{NFE, A}$ mean content of N-free extracts in diets A (in kg (kg DM)$^{-1}$)
$x_{CP, A}$ mean content of crude protein in diets A (in kg (kg DM)$^{-1}$)
$x_{EE, A}$ mean content of ether extract (crude fat) in diets A (in kg (kg DM)$^{-1}$)
τ_2 end of phase A (in d)
τ_1 beginning of phase A (in d)

Equivalent equations are used to describe phases B and C.

The overall emission of a heifer during its entire life is

$$EF_{CH4} = EF_{CH4, A} + EF_{CH4, B} + EF_{CH4, C} \quad (19)$$

where

EF_{CH4} cumulative enteric CH_4 emissions during the period as a heifer (in kg animal^{-1})
$EF_{CH4, A}$ cumulative enteric CH_4 emissions in phase A (in kg animal^{-1})
etc.

2.5 Volatile solids excretion

VS excretion rates are calculated for each phase from feed constituent properties according to Equation (20) (Dämmgen et al., 2011). For phase i, they amount to:

$$VS_i = M_{feed, i} \cdot \left(1 - X_{ash, feed, i}\right) \cdot \left(1 - X_{DOM, i}\right) = \frac{\sum ME_i}{\eta_{ME, i}} \cdot \left(1 - X_{ash, feed, i}\right) \cdot \left(1 - X_{DOM, i}\right) \quad (20)$$

where

VS_i VS excretion rate with faeces during phase i (in kg animal^{-1})

$M_{feed, i}$ feed intake during phase i (dry matter) (in kg animal^{-1})

$X_{ash, feed, i}$ ash content of feed in diet i (in kg kg^{-1})

$X_{DOM, i}$ apparent digestibility of organic matter in diet i (in kg kg^{-1})

$\Sigma ME_{i,}$ cumulative ME requirements in phase i including grazing (in MJ animal^{-1})

$\eta_{ME, i}$ mean ME content of diets i (in MJ kg^{-1})

For each phase, the amounts of VS excreted during grazing have to be determined separately, as the methane conversion factors (MCF) for grazing differ from those for house and storage (IPCC, 2006, Table 10.17 [5)]). However, it remains unknown, which excretions originate from which feed. *This model assumes* therefore that it is adequate to use the fractions $x_{graz, A}$ and $x_{graz, B}$ to derive the shares of the faeces excreted during grazing. For phases A and B, this share is obtained according to

$$VS_{graz, A} = VS_A \cdot x_{graz, A} \tag{21}$$

$$VS_{graz, B} = VS_B \cdot x_{graz, B} \tag{22}$$

where

$VS_{graz, A}$ VS excretion rate with faeces during phase A during grazing (in kg animal^{-1})

VS_A VS excretion rate with faeces during phase A (in kg animal^{-1})

$x_{graz, A}$ fraction of time spent grazing in phase A (in a a^{-1})

etc.

Grazing is not taken into account for phase C (see Fig. 6).

2.6 Nitrogen excretion rates

Overall N excretion rates of faeces and urine can be derived from the element balance (Equation (23)). The basic relation for heifers immediately before first calving is

$$\begin{aligned} m_{excr} &= m_{faec} + m_{ren} = m_{feed} - m_g \\ &= \left(\frac{\sum ME_A}{\eta_{ME, A}} \cdot x_{XP, A} + \frac{\sum ME_B}{\eta_{ME, B}} \cdot x_{XP, B} + \frac{\sum ME_C}{\eta_{ME, C}} \cdot x_{XP, C} \right) \cdot x_{N, XP} - m_g \end{aligned} \tag{23}$$

with

m_{excr} overall N excretion (in kg animal^{-1})

m_{faec} faecal N excretion (in kg animal^{-1})

m_{ren} renal N excretion (in kg animal^{-1})

m_{feed} N intake with feed (in kg animal^{-1})

m_g N retained in the heifer (in kg animal^{-1})

ΣME_A cumulative ME requirements in phase A including grazing (see Equation (14) (in MJ animal^{-1})

η_{ME} mean ME content of diets A (in MJ kg^{-1})

$x_{CP, A}$ mean CP content of diets A (in kg kg^{-1})

$x_{N, CP}$ N content of crude protein ($x_{N, CP}$ = 1/6.25 kg kg^{-1})

etc.

5 CH_4 emissions from storage are calculated using MCFs and VS excretion rates. MCF for regions with cold climate (applies to Germany) according to IPCC (2006): pasture: 0.01 kg kg^{-1}; straw based systems: 0.02 kg kg^{-1}; slurry based system: 0.10 to 0.25 kg kg^{-1}.

The excretion rates for single phases have to be determined accordingly (for phases B and C by analogy):

$$m_{\text{excr, A}} = m_{\text{faec, A}} + m_{\text{ren, A}} = m_{\text{feed, A}} - m_{\text{g, A}} = \frac{\sum ME_{\text{A}}}{\eta_{\text{ME, A}}} \cdot x_{\text{XP, A}} \cdot x_{\text{N, XP}} - m_{\text{g, A}} \quad (24)$$

Different emission factors for grazing and manure management (housing, storage, spreading) are used to quantify emissions of NH_3 and N_2O from the manure management systems. [6] Hence, excretion during grazing has to be determined. Again, *this model assumes* that this can be achieved using the equivalents of Equations (21) and (22) in combination with Equation (24).

$$m_{\text{excr, A}} = m_{\text{excr, house, A}} + m_{\text{excr, graz, A}} \quad (25)$$

and

$$m_{\text{excr, graz, A}} = m_{\text{excr, A}} \cdot x_{\text{graz, A}} \quad (26)$$

$$m_{\text{excr, graz, B}} = m_{\text{excr, B}} \cdot x_{\text{graz, B}} \quad (27)$$

where
$m_{\text{excr, A}}$ N excretion rate for phase A (in kg animal^{-1})
$m_{\text{excr, house, A}}$ N excretion rate for phase A during housing (in kg animal^{-1})
$m_{\text{excr, graz, A}}$ N excretion rate for phase A during grazing (in kg animal^{-1})
$x_{\text{graz, A}}$ fraction of time spent grazing in phase A (in a a^{-1})
etc.

2.6.1 N retained

The final weight of the animal, w_4, is the weight before calving. Hence the amount of N retained in the animal is

$$m_{\text{g}} = (w_4 - w_1) \cdot x_{\text{N, he}} \quad (28)$$

where
m_{g} amount of N retained in the animal (in kg animal^{-1})
w_4 final weight of the heifer (in kg animal^{-1})
w_1 start weight of the heifer (in kg animal^{-1})
$x_{\text{N, he}}$ N content of the heifer (in kg kg^{-1})

The amounts of N retained are calculated for each single phase.

2.6.2 Faecal N excretion

Daily excretion of faecal N is obtained as described in Poulsen and Kristensen (1998) as a function of both the N and the DM matter intake rates.

6 For other cattle (including heifers), the EMEP (2013) partial emission factors for NH_3 can be combined to about 0.5 kg kg^{-1} for German housed animals and the subsequent manure management, whereas typical losses on pasture amount to 0.06 kg kg^{-1} (both emission factors related to total ammoniacal nitrogen (TAN) excreted).

$$m_{\text{faec, d}} = a_{\text{faec}} \cdot m_{\text{feed, d}} + \left(b_{\text{faec}} \cdot M_{\text{feed, d}} + c_{\text{faec}} \cdot M_{\text{feed, d}}^{2}\right) \cdot x_{\text{N, CP}} \quad (29)$$

where

$m_{\text{faec, d}}$	daily N excretion of faeces (in kg animal^{-1} d^{-1})
a_{faec}	constant (a_{faec} = 0.04 kg kg^{-1})
$m_{\text{feed, d}}$	daily N intake of feed (in kg animal^{-1} d^{-1})
b_{faec}	constant (b_{faec} = 0.02 kg kg^{-1})
$M_{\text{feed, d}}$	daily dry matter intake (in kg animal^{-1} d^{-1})
c_{faec}	constant (c_{faec} = 0.0018 kg^{-1} animal d)
$x_{\text{N, CP}}$	N content of crude protein ($x_{\text{N, CP}}$ = 1/6.25 kg kg^{-1})

This non-linear equation can be expressed in terms of ME intake and, by analogy to the equation of cumulative ME intake (Equation (11)), be processed to obtain an equation of the cumulative excretion of faecal N (valid for constant Δw only):

$$\sum m_{\text{faec}} = \frac{1}{\Delta w} \cdot \left[p \cdot \left(w_4 - w_1\right) + \frac{q}{2} \cdot \left(w_4^2 - w_1^2\right) + \frac{r}{3} \cdot \left(w_4^3 - w_1^3\right)\right] \quad (30)$$

where

Σm_{faec}	cumulative excretion of faecal N of a heifer (in kg animal^{-1})
Δw	daily weight gain (in kg animal^{-1} d^{-1})
p	coefficient (in kg animal^{-1})
w_4	final weight of heifer (in kg animal^{-1})
w_1	start weight of heifer (in kg animal^{-1})
q	coefficient (in kg kg^{-1} animal^{-1})
r	coefficient (in kg kg^{-2} animal^{-1})

The coefficients p, q and r are defined as follows:

$$p = A \cdot a + B \cdot a^2 \quad (31)$$

$$q = A \cdot b + 2\, B \cdot a \cdot b \quad (32)$$

$$r = B \cdot b^2 \quad (33)$$

with a and b as defined by Equations (12) and (13), and

$$A = \frac{a_{\text{faec}} \cdot x_{\text{N, DM}} + b_{\text{faec}} \cdot x_{\text{N, CP}}}{\eta_{\text{ME}}} \quad (34)$$

$$B = \frac{c_{\text{faec}} \cdot x_{\text{N, CP}}}{\eta_{\text{ME}}^2} \quad (35)$$

where

a_{faec}	constant (a_{faec} = 0.04 kg kg^{-1})
$x_{\text{N,DM}}$	N content of feed dry matter (in kg kg^{-1})
b_{faec}	constant (b_{faec} = 0.02 kg kg^{-1})
c_{faec}	constant (c_{faec} = 0.0018 kg^{-1} animal d)
$x_{\text{N, CP}}$	N content of crude protein ($x_{\text{N, CP}}$ = 1/6,25 kg kg^{-1})
η_{ME}	ME content of feed dry matter (in MJ kg^{-1})

Equation (30) is used to calculate excretion for single feeding phases.

2.6.3 Renal N excretion

For each phase, renal N excretion (so-called total ammoniacal nitrogen, TAN) is obtained from the overall and the faecal N according to

$$m_{\text{TAN, A}} = m_{\text{excr, A}} - m_{\text{faec, A}} \quad (36)$$

where

$m_{\text{TAN, A}}$	amount of N in urine excreted during phase A (in kg animal^{-1})
$m_{\text{excr, A}}$	cumulative amount of N excreted during phase A (in kg animal^{-1})
$m_{\text{face, A}}$	amount of N in faeces excreted during phase A (in kg animal^{-1})

and similarly for phases B and C.

3 Sensitivity analysis

3.1 Definition of standard heifer input parameters

3.1.1 Animal weights, weight gain and share of grazing – the basic data set

The **start weight** w_1 is given by the final weight of calves. As in Dämmgen et al. (2013) we use 125 kg animal^{-1}. The **final weight**, w_4, is 625 kg animal^{-1}. The time spent as a heifer is 730 d or 24 months (see Figure 1). Hence, the **weight gain** amounts to 685 g animal^{-1} d^{-1}. This leads to the following set of times and weights:

	days		kg animal^{-1}
τ_1	0	w_1	125
τ_2	365	w_2	375
τ_3	669	w_3	583
τ_4	730	w_4	625

Table 2

Composition of diets, contents related to dry matter (for sources see text)

	constituent	share	ME content	digestibility of organic matter	contents [kg kg^{-1}]				
		kg kg^{-1}	MJ kg^{-1}	kg kg^{-1}	crude protein	crude fibre	nutrient free extracts	ether extract	crude ash
diet A (house)	grass silage	0.40	10.0	0.72	0.162	0.245	0.452	0.042	0.099
(also diet C)	maize silage	0.47	10.2	0.73	0.080	0.228	0.582	0.028	0.082
	concentrate *	0.13	12.3	0.83	0.205	0.143	0.554	0.042	0.065
	mineral mixture	0.01	0.0		0.000				
mean			10.3	0.73	0.128	0.221	0.532	0.035	0.086
diet A (grazing)	pasture grass	0.90	10.0	0.72	0.180	0.225	0.430	0.040	0.125
	concentrate	0.10	12.3	0.83	0.205	0.143	0.554	0.042	0.065
mean			10.2	0.73	0.182	0.216	0.442	0.040	0.119
diet B (house)	grass silage	0.988	10.0	0.72	0.162	0.245	0.452	0.042	0.099
	straw	0.010	6.4	0.45	0.038	0.450	0.425	0.017	0.070
	mineral mixture	0.002	0.0		0.000				
mean			9.9	0.71	0.161	0.242	0.451	0.042	0.098
diet B (grazing)	pasture grass	1.00	10.0	0.72	0.180	0.225	0.430	0.040	0.125

* standard concentrate MLF 18/3 (Milchleistungsfutter 18/3)

The mean **share of grazing,** x_{graz}, is set to 0.2 a a^{-1} (German mean, see Figure 5).

3.1.2 Nitrogen contents of heifers and calves

Data sets containing N contents of heifers were collated by Janssen (2006). The analysis of these data sets resulted in a correlation between daily weight gains and CP retained that suggests an N content of 0.0244 kg kg^{-1}. This N content is used in the subsequent calculations. [7)]

3.1.3 Diet composition and feed properties

Information on diet composition, in particular on ME and CP contents as well as dry matter intake rates, were provided in Warzecha et al. (2002); Weiß et al. (2005); Kirchgeßner et al. (2008). Gross energy contents of the feed constituents had to be collated from Beyer et al. (2004). The calculations use the standard feed properties applied in the German agricultural emission inventory (Rösemann et al., 2015) as listed in Table 2.

3.2 Sensitivity of the model

The model should reflect the effect of important variables such as weight gain and final weight. It should also be insensitive to small changes in intermediate entities such as the intermediate weight w_2.

[7] The N contents of dairy cows as provided by DLG (2005) are slightly higher ($X_{N, he}$ = 0.0256 kg kg^{-1}). DLG (2014) has 0,025 kg kg^{-1} for dairy cattle irrespective of subcategories.

3.2.1 Variation of daily weight gains

For a given final weight, increasing daily weight gain leads to a shorter lifespan implying decreasing overall ME requirements. This is because overall ME required for maintenance decreases with decreasing lifespan. Lower ME requirements result in to lower overall feed intake and therefore decreasing CH_4 emissions from enteric fermentation as well as VS and N excretion per animal. A 5 % increase in weight gains results in reductions of 3 % for enteric CH_4, 2 % for VS, 3 % for total N and TAN. Figure 7 shows the results of model calculations for a final weight of 625 kg animal^{-1} for housed heifers (x_{graz} = 0 a a^{-1}).

3.2.2 Variation of final weights

Increased final weights result in increased energy requirements and feed intake if weight gains are kept constant (Δw = 0.685 kg animal^{-1} d^{-1}, x_{graz} = 0.2 a a^{-1}). Hence, all excretion rates will increase: A 5 % increase in final weights results in increased excretion rates of 9 % for enteric CH_4, 10 % for VS, total N and TAN. The results are illustrated in Figure 8.

3.2.3 Variation of the fraction of grazing

If weight gains and final weights are kept constant (Δw = 0.685 kg animal^{-1} d^{-1}, w_4 = 625 kg animal^{-1}), grazing has a major effect on N excretion rates. It can be seen that the extension of the grazing period is unfavourable for N excretion, as pasture grass has a comparatively higher CP content. In addition, an adequate ME supply in phase B presupposes higher dry matter intake. If the grazing time is extended by one month, both N

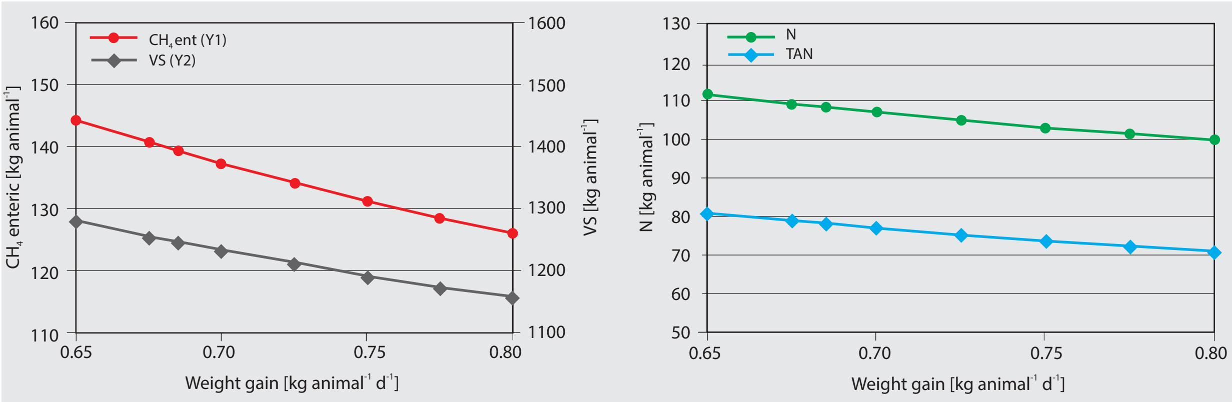

Figure 7
Variation of CH_4, VS and N excretion as a function of daily weight gains Δw

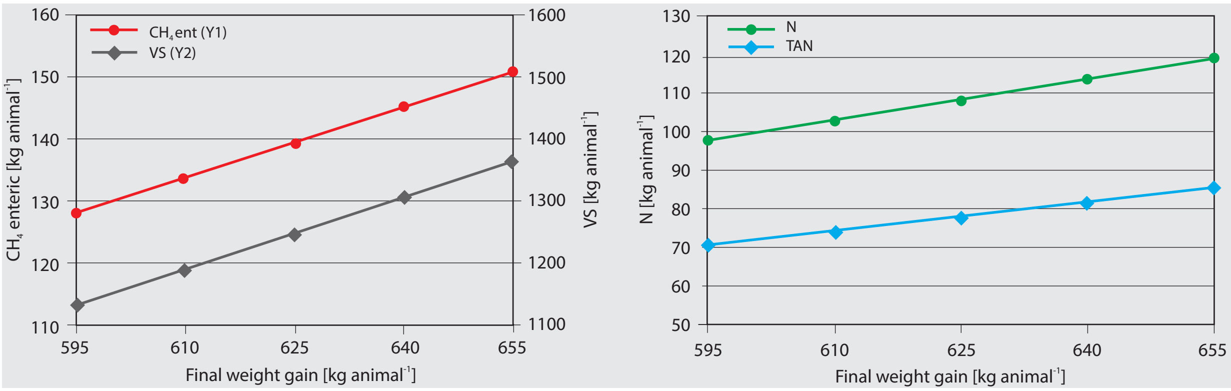

Figure 8
Variation of CH_4, VS and N excretion as a function of final weight w_4

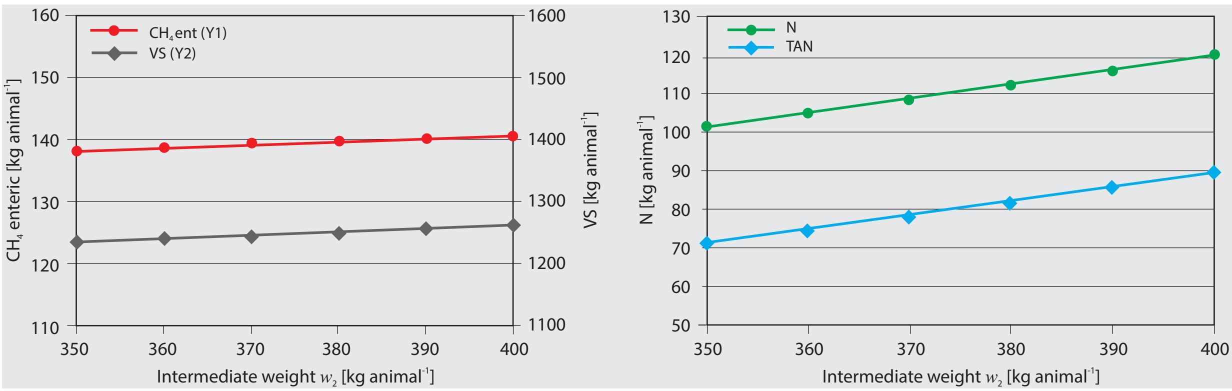

Figure 9
Variation of CH_4, VS and N excretion as a function of the fraction of time spent grazing, x_{graz}

and TAN excretion increase by about 5 %. The effect on enteric CH_4 emissions and VS excretion is marginal (Figure 9).

3.2.4 Variation of the intermediate weight w_2

The intermediate weight w_2 marks the transition from phase A to phase B, i.e. from higher ME contents to lower ones. A change in w_2 (375 kg animal^{-1}) by 5 % is equivalent to about a month spent in the respective phase. Weight gain and final weight w_4 were kept constant (Δw = 0.685 kg animal^{-1} d^{-1}, w_4 = 625 kg animal^{-1}). An overall grazing fraction x_{graz} of 0.2 a a^{-1} (German mean, see Figure 5) was used. As can be seen from Figure 10, a change in w_2 results in a minor change of CH_4 emissions (<1 kg animal^{-1}) and of VS excretion (1 %). Reduction by 5 % yields an increase of less than 1 % in N and TAN excretion, and vice versa.

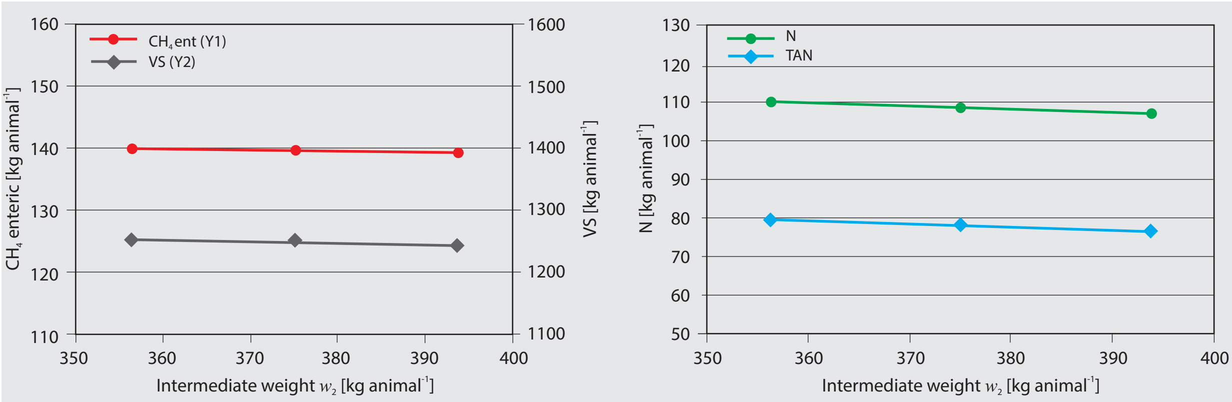

Figure 10
Variation of CH_4, VS and N excretion as a function of the intermediate weight w_2

3.2.5 Variation of the amount of nitrogen retained

With the large amount of N taken in (about 100 kg animal^{-1}), the amount retained is comparatively small (about 12 kg animal^{-1}). Figure 11 illustrates that changes of about 5 % in the N content of the animal, $x_{N, he}$, have almost no influence on the amounts of N excreted (data for Δw = 0.685 kg animal^{-1} d^{-1}, w_4 = 625 kg animal^{-1}, x_{graz} = 0.2 a a^{-1}).

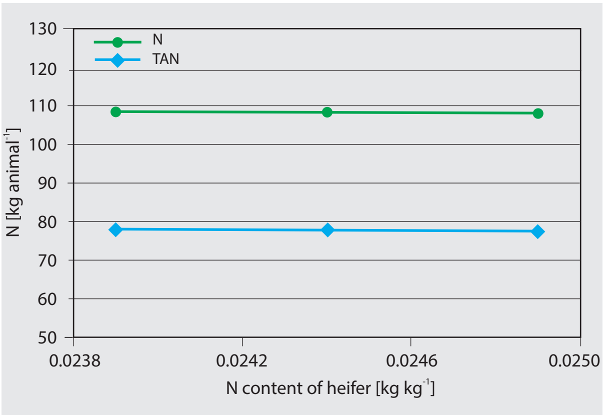

Figure 11
Variation of N excretion as a function of the N content of the heifer, $x_{N, he}$

4 Discussion

4.1 Uncertainties of input variables

4.1.1 ME requirements

The basic tool used in the present calculations was developed from Table 1 provided by GfE (2001) with additions by Kirchgeßner et al. (2008). GfE (2001) gives no information on uncertainties. Table 1 is the *only* official data set available. This table lists daily ME requirements which are themselves modelled from the requirements for the daily gains of protein, fat and energy. The relevant data base is more than two decades old and does not reflect current animal weights. No comparison with experimental data is described. This situation is highly unsatisfactory. Nevertheless, this table is used in all relevant publications and official recommendations in Germany, e.g. DLG (2008) and KTBL (2014).

4.1.2 Feeding phases and grazing

The assumptions on feeding phases are based on information given in recommendations (DLG, 2008), supplemented by Le Cozler et al. (2008) and Benson (2011) and backed up by expert judgement (Martin, Lange, see above). No uncertainties have been reported.

4.2 Comparison of the results with data provided in the literature

It is obvious that the **ME requirements** are identical with those provided in the official GfE documentation they were derived from. The results obtained with the model agree well with the ME requirements given in DLG (2014) (55 GJ animal^{-1} ME per heifer plus calf). Rutzmoser and Ettle (2012) found that experimental ME intake rates concur well with GfE data for weights between 100 and 450 kg animal^{-1}, and fall below them at higher weights (about 10 % for 550 kg animal^{-1}). The comparison is aggravated by the fact that for high animal weights weight gains are not constant and much higher than those used in the present model. It remains uncertain whether or not a linear extrapolation is adequate and – if not – how large potential errors are.

The **enteric CH_4 emissions** calculated using this model exceed those which use the default methane conversion factor (MCF) provided in IPCC (2006). The latter are obtained as fraction of the energy equivalent of CH_4 of the gross energy (GE) intake (0.065 ± 0.01 MJ MJ^{-1} for cattle in developed countries). The MCF obtained with the model in this work ranges between 0.082 MJ MJ^{-1} and 0.085 MJ MJ^{-1} (Table 3). If one accepts the validity of the approach of Kirchgessner et al. (1995) which passed international tests (see discussion in Dämmgen et al., 2012) then the IPCC methodology appears to be inadequate for German dairy heifers.

VS excretion rates for comparison could not be identified in the literature.

N excretion rates fit the official German recommendations published in DLG (2014) almost exactly. The German Ministry for Nutrition, Agriculture and Consumer Protection (BMELV, 2007) recommends to use 60 kg animal^{-1} a^{-1} for a grassland based production and 42.7 kg animal^{-1} a^{-1} production without grassland for the lifespan of a heifer. [8)]

4.3 Emission reduction potentials

The example calculations of emission reduction potentials shown in Table 3 reveal just one clear option: For given final weights, increased daily weight gains might help reduce ME required for maintenance, emissions per animal and – as will be seen – costs per animal.

Figure 8 suggests that decreased final weights might be an option for emission reduction. However, lower final weights of heifers equate lower start weights of dairy cows, which also means smaller rumens. In practice, milk production aims at high milk yields per cow, which presupposes a high-volume rumen to guarantee a sufficient feed intake rate.

Figure 2 illustrates that present mean weight gains fall below 0.7 kg animal^{-1} d^{-1}. Official N excretion rates recommended by BMELV (2007) use a weight gain of about 0.85 kg animal^{-1} d^{-1}, suggesting that this increase is feasible. This is supported by the following: Heifers should have a weight of about 400 kg animal^{-1} when they are first inseminated. This would result in a weight of first calving of 600 to 650 kg animal^{-1}. Hoffmann (2001) collated data that show that the animal weight is the crucial entity for successful insemination and pregnancy. The above mentioned weights can be strived for in a time span of 20 to 22 months with a moderate increase of weight gains to about 0.80 kg animal^{-1} d^{-1}. Carefully composed diets combined with adequate grazing will prevent them from adiposity and at the same time have positive influence on health, performance level and longevity of cows and on the economic results of milk production (e.g. Drackley, 2005). Losand (2009) reported that the exhaustion of the growth potential had also beneficial effects on fertility and calving as well as milk yield in the first lactation period.

Increased weight gains of about 9 % result in excretions and emissions that are reduced by about the same amount. Reduced cumulative ME requirements also mean reduced feed intake, and this results in a reduction of costs per heifer. For Simmental heifers, Spiekers (2013) reported a decrease of feed costs of about 50 Euros per month not needed to rear heifers.

Table 3
Effects of increased weight gains and extended grazing period on excretions and emissions [9)]

		x_{graz} = 0.20 a a^{-1}		x_{graz} = 0.30 a a^{-1}	
Δw	kg animal^{-1} d^{-1}	0.7	0.8	0.7	0.8
emissions					
CH_4 enteric	kg animal^{-1}	137	126	138	127
DM intake	kg animal^{-1}	4972	4667	5023	4715
VS excreted	kg animal^{-1}	1235	1159	1242	1166
N excreted	kg animal^{-1}	107.3	100.1	111.1	103.6
TAN excreted	kg animal^{-1}	77.4	71.2	81.0	74.6
CH_4 manure management *	kg animal^{-1}	14.6	13.7	13.0	12.1
NH_3 manure management *	kg animal^{-1}	35.1	32.3	32.2	29.6
N_2O manure management	kg animal^{-1}	0.59	0,55	0,53	0.49
GHG	kg animal^{-1} CO_2-eq	3977	3659	3932	3617
characteristic entities					
methane conversion factor **	MJ MJ^{-1}	0.085	0.083	0.084	0.082
TAN content ***	kg kg^{-1}	0.72	0.71	0.73	0.72

* includes emissions during grazing; ** according to IPCC, see text; *** ratio of TAN excreted to total N excreted.

Table 3 also shows the effect of increased grazing. Grazing reduces both GHG and NH_3 emissions. Extended grazing does not really affect CH_4 emissions from enteric fermentation if one uses the diets described in Table 2. DM intake is slightly higher, and so are VS and N excretions. However, CH_4 emissions from storage and NH_3 and N_2O emissions from manure management are affected favourably.

[8] BMELV (2007) provides excretion rates for dairy heifers plus calves and an overall life span of 27 months. Excretion rates for calves are also listed. Hence the annual excretion rate is obtained as

$$m_{\mathrm{N,\,heifer}} = \frac{m_{\mathrm{N,\,ya}} - m_{\mathrm{N,\,calf}}}{\Delta t_{\mathrm{heifer}}}$$

where
$m_{N,heifer}$ amount of N excreted by a heifer per year (in kg animal^{-1} a^{-1})
$m_{N,ya}$ amount of N excreted per young animal (0 to 27 months) (in kg animal^{-1})
$m_{N,calf}$ amount of N excreted per calf (0 to 4 months) (in kg animal^{-1})
Δt_{heifer} life span of a heifer (23 months)

Back-calculations show that this data was obtained for a weight gain of about 0.850 kg animal^{-1} d^{-1}. With the assumption that the N excretion of a calf is 5.1 kg animal^{-1}, these excretion rates match those obtained in this model sufficiently, keeping in mind that marginal weights are not identical and that no diet composition is mentioned.

[9] Conditions for the calculation of emissions: loose housing, slurry; storage: conventional tank with natural crust; half of the slurry broad cast on short grass, the other half spread on arable land using trailing hoses, incorporation within 4 h. Emission factors as in IPCC (2006) and EMEP (2013); global warming potentials of 25 and 298 kg kg^{-1} CO_2-eq for CH_4 and N_2O, respectively, as in IPCC (2007).

Appendices

Appendix 1 A steady equation for daily ME requirements of housed animals

An analysis of Table 1 reveals that for each weight gain Δw the daily ME requirements are almost linear functions of the actual weights:

$$ME = a + b \cdot w \quad \text{(A1)}$$

where
ME daily ME requirements (in MJ animal^{-1} d^{-1})
a constant (in MJ animal^{-1} d^{-1}, see Table A1)
b coefficient (in MJ kg^{-1} d^{-1}, see Table A1)
w actual weight (in kg animal^{-1})

Table A1
Numerical values of the constant a and the coefficient b in Equation (A1)

Δw kg animal^{-1} d^{-1}	constant a MJ animal^{-1} d^{-1}	coefficient b MJ kg^{-1} d^{-1}	R^2
0.40	13.5928571	0.1129286	0.9999
0.50	12.1400000	0.1262667	0.9998
0.60	11.8872727	0.1384606	0.9999
0.70	11.2090909	0.1530424	0.9999
0.80	10.6844444	0.1676000	0.9999
0.90	9.1500000	0.1856667	0.9998
1.00	6.8285714	0.2065000	0.9997

Both a and b can be expressed as functions of Δw. As shown in Figure A1, non-linear regressions are needed to best reproduce the values of the table. The values for Δw = 0.4 kg animal^{-1} d^{-1} are considered outliers. Figure 2 illustrates that they can be neglected for this study as a weight gain of Δw = 0.4 kg animal^{-1} d^{-1} is irrelevant. It has to be kept in mind that the relations in Table A1 apply to housed animals without any grazing.

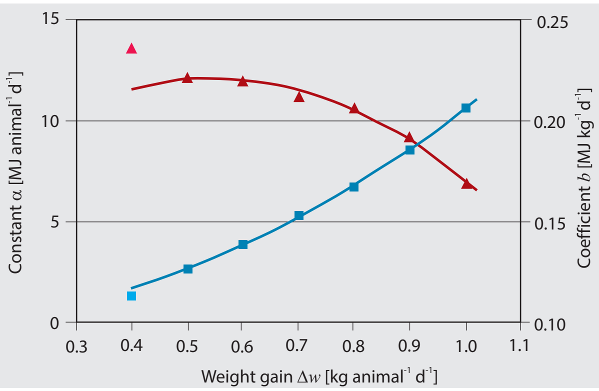

Figure A1
Constant a (triangles) and coefficient b (circles) in Equation (A1) as functions of weight gain Δw

constant $$a = \alpha + \beta \cdot \Delta w + \gamma \cdot \Delta w^2 \quad \text{(A2)}$$

coefficient $$b = \delta + \varepsilon \cdot \Delta w + \zeta \cdot \Delta w^2 \quad \text{(A3)}$$

with
a constant (in MJ animal^{-1} d^{-1}, see Equation (A1))
α constant (α = 4.7665678 MJ animal^{-1} d^{-1})
β coefficient (β = 26.7961752 MJ kg^{-1})
Δw daily weight gain (in kg animal^{-1} d^{-1})
γ coefficient (γ = -24.5867088 MJ animal kg^{-2} d)
b coefficient (MJ kg^{-1} d^{-1}, see Equation (A1))
δ constant (δ = 0.097908 MJ kg^{-1} d^{-1})
ε coefficient (ε = 0.0061962 MJ animal kg^{-2} d^{-2})
ζ coefficient (ζ = 0.1020296 MJ animal^2 kg^{-3} d)

Regression coefficients R^2 for Equations (A2) and (A3) are 0.9902 and 0.9997, respectively. Figure A2 illustrates the usefulness of this approach.

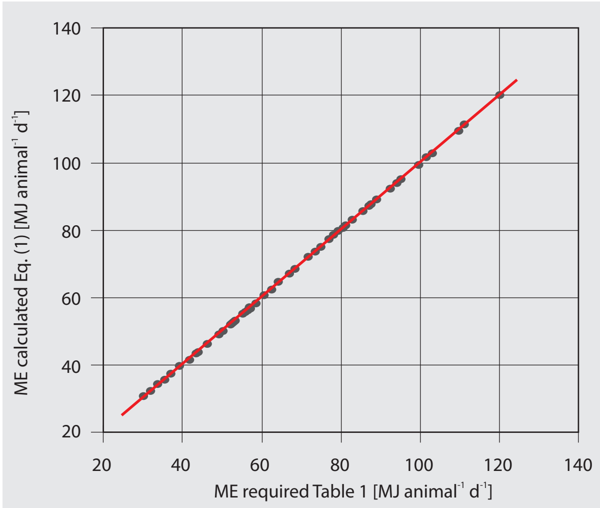

Figure A2
Comparison of daily ME requirements in Table 1 (data for Δw = 0.4 kg animal^{-1} d^{-1} excluded) and as calculated using Equations (A1) to (A3) (slope: 0.9997; offset: 0.016 MJ animal^{-1} d^{-1}; R^2 0.9999)

Appendix 2 Cumulative ME requirements of housed animals

Equation (A1) was used to establish a list of ME requirements for each single day between start weight and final weight, using a start weight of 125 kg animal^{-1} (the final weight of calves in the German inventory). Adding up the single-day ME requirements over the heifers' entire life span as function of Δw and w_{fin} leads to the cumulative requirements. These are presented in Table A2.

Table A2

Cumulative ME requirements of heifers (in GJ animal⁻¹)

final weight w_{fin} (kg animal⁻¹)	daily weight gain Δw (kg animal⁻¹ d⁻¹)							
	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85
300	13.65	12.81	12.13	11.50	11.00	10.53	10.17	9.81
350	18.97	17.82	16.86	16.04	15.33	14.76	14.21	13.78
400	24.92	23.43	22.17	21.14	20.27	19.52	18.85	18.28
450	31.50	29.64	28.12	26.80	25.68	24.74	23.93	23.21
500		36.46	34.57	33.02	31.72	30.57	29.63	28.75
550			41.60	39.79	38.21	36.94	35.75	34.81
600					45.24	43.74	42.51	41.39
650						51.18	49.68	48.50
700							57.49	56.13

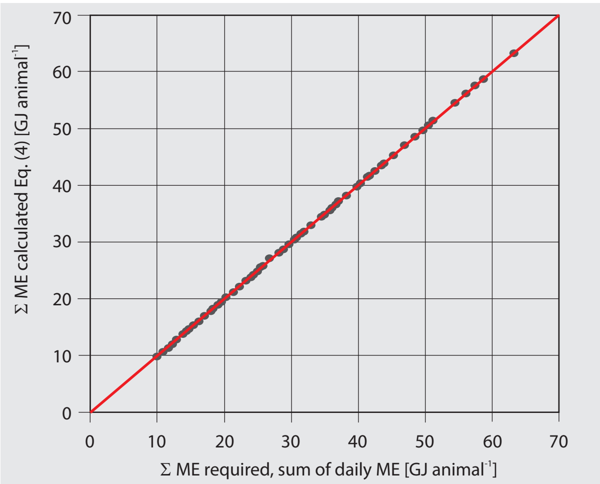

Figure A3

Comparison of cumulative ME requirements obtained from adding up single-day ME requirements and using Equation (A4) (slope: 1.0009; offset: 0.0031 GJ animal⁻¹; R^2 1.0000)

Cumulative ME requirements can also be obtained from the application of Equation (A4). This Equation is derived from Equation (A1) by integration using the approach described in the appendix in Haenel et al. (2011). Figure A3 shows that the results are almost identical to that obtained by adding up single-daily ME requirements.

$$\sum ME = \frac{1}{\Delta w}\cdot\left[a\cdot\left(w_4 - w_1\right) + \frac{b}{2}\cdot\left(w_4^2 - w_1^2\right)\right] \quad \text{(A4)}$$

where

ΣME cumulative ME requirements (in MJ animal⁻¹)

Δw daily weight gain (in kg animal⁻¹ d⁻¹)

a coefficient (in MJ animal⁻¹ d⁻¹, see Equation (A2))

w_4 final weight of heifer (in kg animal⁻¹)

w_1 start weight of heifer (in kg animal⁻¹)

b coefficient (in MJ kg⁻¹ d⁻¹, see Equation (A3))

It can be shown that the cumulative ME requirements for any subsection of the heifers' life span (i.e. any phase) can be described by an equation of the same type as Equation (A4) using the appropriate weight gains Δw and initial and final weights, w_m and w_n, respectively. Note that Δw is assumed to be constant over the period considered.

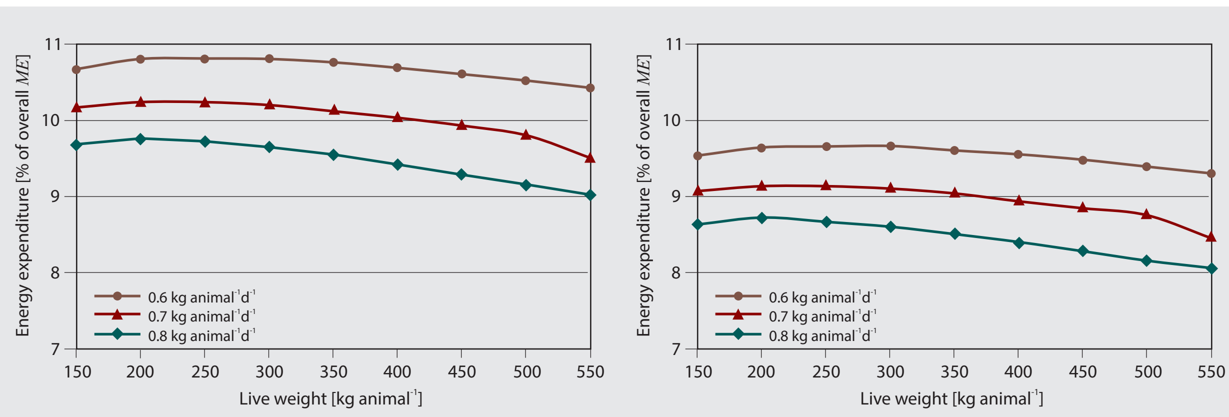

Figure A4

Energy expenditure due to grazing in per cent of ME_o (overall ME), for various live weights and weight gains. Left: using IPCC (2006) default value; right: using DLG (2014) recommendation.

Appendix 3 Energy expenditure related to overall ME intake

IPCC (2006) and DLG (2014) provide factors to estimate energy expenditure for grazing. Whereas IPCC (2006) gives a general estimate for all cattle of 17 % of the ME required for maintenance, ME_m, GfE (2001) states that grazing heifers may result in increased ME_m demands of *up to* 15 %. The energy expenditure may have to be related to overall ME requirements, $ME_{overall}$, if ME_m is not available.

GfE (2001) provides tables for both requirements: Table 1.5.2 gives ME_m requirements as a function of live weight, Table 1.5.3 contains $ME_{overall}$ requirements as a function of live weight and weight gain. This data was used to derive a factor characterising energy expenditure relative to the overall ME requirements of dairy heifers.

The comparison in Figure A4 illustrates that both procedures deviate from 10 % by about ±1 % in any case. A factor of 1.1 MJ MJ^{-1} for total ME requirements taking primarily the national recommendation into account is conservative.

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