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Allocation of environmental burdens in dairy systems: Expanding a biophysical approach for application to larger meat-to-milk ratios

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HIGHLIGHTS

- The standard method for the allocation of emissions to meat and milk is limited.
- It may lead to wrong conclusions when assessing mitigation measures.
- A new approach is developed based on energy requirements for milk and meat.
- Its validity is demonstrated by applying it on a variety of dairy farms worldwide.
- Increasing cow longevity reduced emissions only when applying the new approach.

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ABSTRACT

The dairy sector is urged to reduce environmental impacts, such as greenhouse gas (GHG) emissions. But dairy farms not only produce milk: surplus calves and culled cows also yield meat as co-product. To split environmental impacts between milk and meat, a biophysical allocation method proposed by the International Dairy Federation (IDF) is currently used. Its applicability to farms with large meat-to-milk output ratios (beef-to-milk ratio, BMR) may be limited and lead to wrong conclusions when assessing GHG emissions and mitigation measures at farm level.

To overcome these limitations, we developed a biophysical allocation approach based on the net energy requirement for milk and meat production according to internationally agreed energy requirements for dairy cows. Both the enhanced and the existing allocation methods were tested on an international dataset that included farms with a large range of BMR, as can be found in dual-purpose production systems or on farms with low milk productivity. The results from the international dataset reveal that the allocation factor does not substantially change for production systems with low BMR. For BMR up to 0.03 kg live weight (LW)/kg of fat- and protein-corrected milk (FPCM), the maximum deviation in the allocation factor between the two methods was 0.047. For larger BMR, the developed method still allocated relevant shares of emissions to meat while the standard approach did not. The developed method is less sensitive to shifts in BMR, especially for low-performing dairy farms.

In addition, both methods were tested on a dataset of 46 Swiss dairy farms. By increasing the longevity of cows (one additional lactation), the impacts of altered BMR on the modelled GHG emissions and their allocation on milk and meat could be assessed. Increased longevity resulted in fewer cows to be replaced, decreased emissions from the rearing of replacement stock (-444 kg CO_2-equivalents/cow/year) and lower meat output (-61 kg LW/cow/year), as fewer cows were culled. Consequently, a larger share of emissions was allocated to milk. While the standard biophysical allocation approach did not result in reduced GHG emissions per kg of milk (+0.002 kg CO_2-equivalents/kg FPCM), the newly developed approach generated a modest (-0.022 kg CO_2-equivalents/kg FPCM), although not significant reduction.

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The effects of GHG mitigation measures that affect BMR are thus represented more accurately than when applying the standard approach. Based on the presented data, we encourage the revision of currently used international standards for allocating environmental impacts to milk and meat.

1. Introduction

In addition to many socio-economic (e.g. nutrition, income, ecosystem services) and cultural benefits, dairy production is also associated with important environmental impacts (Dumont et al., 2019). Dairy cattle emit approximately 40% of global livestock greenhouse gases (GHG) (Gerber et al., 2013), contributing significantly to climate change. Climate-relevant emissions include mainly the short-lived, potent GHG methane (from enteric fermentation and manure handling), nitrous oxide emissions from manure management but also carbon dioxide emissions from energy use, input production or land-use change (Rotz, 2018). Quick and decisive reduction pathways for all climate-relevant gases are urgent to hold the global warming potential below critical thresholds (IPCC, 2021). Following the Paris Agreement, 92 countries have determined GHG reduction goals for the livestock sector (FAO and GDP, 2018) and the dairy industry has committed to outlining a pathway to net zero (GDP, 2021).

But dairy farms not only produce milk: depending on the degree of specialisation on dairy farms, relevant amounts of meat as by-product also result. For instance, culled cows and surplus calves from dairy farms contribute to about 70% of German beef production (Zehetmeier et al., 2012). Accordingly, a share of the environmental impacts of dairy farms also needs to be attributed to the co-product meat.

A procedure to allocate environmental impacts to a multi-output process (such as a dairy farm) is proposed in the ISO standard on life cycle assessments (ISO, 2006) and briefly summarised here:

- Before allocation methods are applied, the choice of system boundary should aim to obviate the necessity of allocation. For dairy production systems, this requires the application of a system expansion approach as introduced by Cederberg and Stadig (2003). Environmental impacts avoided by the co-product meat (through not producing beef in pure beef systems) can thus be credited to milk production. The system expansion approach requires system boundaries to be drawn beyond the actual farm gate. It thus relies on a vast amount of additional data and assumptions that often cannot be influenced on-farm (Thomassen et al., 2008).
- If system expansion is not feasible, allocation should, according to the ISO standard, be carried out according to underlying physical relationships. That could be mass allocation according to the protein or energy content of the output products or the feed used for lactation (milk) and body growth (meat).
- Although very often applied, ‘other relationships’ (such as economic allocation) are considered only as third choice.

Several authors (Cederberg and Stadig 2003, Rotz et al. 2010, Flysjö et al. 2012, Thoma et al. 2013, O’Brien et al. 2014) have compared system expansion with different approaches to physical and economic allocation. All authors found that the chosen allocation method strongly affects the amount of environmental impacts allocated to milk, but even more so to meat. Impacts allocated to milk were found to be lowest with system expansion, followed by biophysical allocation (based on the energy or protein content of the products or the utilisation of feed energy), while allocation according to economic aspects usually led to higher environmental impacts of dairy production. There is still controversy as to which of these methods is preferable. While O’Brien et al. (2014) advocated for allocation based on economic or biological properties, Mackenzie et al. (2017) contested the superiority of the biophysical allocation approach from a methodological perspective.

Both the International Dairy Federation (IDF) and the European Commission (EC) have encouraged harmonisation by setting the system boundary for life cycle assessments to the farm gate in their guidelines (IDF, 2015; EDA, 2018) and are proposing the biophysical allocation method of Thoma et al. (2013). This approach allocates environmental impacts according to the proportion in which the net energy in feed was used for lactation (milk) and growth (meat). The meat-to-milk ratio (originally beef-to-milk ratio (BMR)) relates sold meat (kg live weight (LW)) to produced milk (kg of fat and protein corrected milk (FPCM)). A dataset of US dairy farms was used to empirically develop a linear relationship between the BMR and the factor of farm emissions allocated to milk (AF_{milk}). Considering the mainly low BMR in the dataset, the validity range of the linear regression equation proposed by Thoma et al. (2013) is restricted to low BMR, meaning to farms with low amounts of meat output per kg milk produced. These low BMR in the dataset can be explained by the exceptionally specialised production processes of US dairy farms. However, in many countries, less specialised dairy farms exist and often generate larger shares of the by-product meat as a consequence of relatively low milk performance. This applies for example to the traditional use of dual-purpose breeds in the Alpine area (i.e. Switzerland, see Averdunk and Krogmeier (2011)), but to an even greater extent to farms in a variety of developing countries. These systems may thus be insufficiently represented by the training dataset used to develop the regression that supports the standard biophysical allocation method as recommended by IDF and the European Commission.

Promising strategies to reduce the environmental impacts of dairy farms will often affect both milk and meat output. Some strategies reduce the impacts of both outputs proportionally (for instance where feed supplements reduce enteric methane production). Other strategies, however, have impacts on milk and meat that are more difficult to quantify: Increased longevity of dairy cows, for instance, will reduce rearing emissions, as less young stock needs to be raised to replace culled cows (Knapp et al., 2014). However, fewer culled cows also result in less meat output at farm level. While overall farm-level emissions decrease, BMR also decreases, and a higher share of the emissions will typically be allocated to milk. The aim of this paper is therefore to develop an expanded biophysical approach that is suited to cover dairy farm cases with elevated beef-to-milk output proportions. Nemecek and Thoma (2020) proposed to allocate according to the respective net energy requirement for milk and body mass growth. We followed this idea here but refined the computations and set the system boundary to the farm gate (excluding the fattening of surplus calves). Further we investigate how

(a) the recommended standard biophysical allocation method (IDF, 2015) fits for lower yielding and dual-purpose production systems, based on two independent datasets;
(b) increased longevity of cows affects the share of environmental impacts allocated to milk.

2. Materials and methods

Two datasets were used to calculate the BMR and develop an expandable allocation approach: the first dataset is based on Swiss dairy farms (Table 1), consisting of both specialised dairy and typical dual-purpose breeds (see section 2.3). The second dataset was collected from the supply chain of the global food company Nestlé, which maintains fresh milk supply chains in about 25 countries from the Americas, Africa, Europe, and Asia (see section 2.4).

Table 1
Mean, standard deviation (±), minimum (Min) and maximum (Max) of key input data from the Swiss farm dataset (n=46) used for modelling greenhouse gas emissions.

Item	Mean (±)	Min	Max
Milk performance (kg FPCM[1]/cow/year)	7231 (1430)	4329	10725
Average number of lactations	3.0 (0.7)	1.4	4.7
First calving age (days)	831 (52)	726	1035
Live weight cow (kg)	672 (46)	600	780
DM intake/cow/day	17.5 (2.1)	12.5	22.0
Diet composition (fraction of yearly DM[2] intake)			
Pasture	0.24 (0.11)	0	0.52
Forage	0.57 (0.11)	0.29	0.76
Corn	0.08 (0.09)	0	0.33
Concentrates	0.11 (0.04)	0.03	0.21
Others	0.04 (0.04)	0	0.17
Net energy lactation of the feed ration, MJ/kg DM	6.29 (0.16)	5.87	6.66
Crude protein of the feed ration, g/kg DM	165 (11)	139	190
Manure storage system (fraction of total excretion)			
Slurry storage covered	0.43 (0.26)	0	0.97
Slurry storage uncovered	0.08 (0.20)	0	0.81
Solid manure storage	0.27 (0.23)	0	0.83
Excreted on pasture	0.22 (0.08)	0.03	0.46

[1] Fat and protein corrected milk
[2] Dry matter

2.1. System boundary of the dairy farm

The system boundary was set to the farm gate according to IDF (2015) guidelines and includes, following a life cycle assessment (LCA) approach, all upstream services (such as the rearing of replacement stock) and the advance emissions of resources used on farm (e.g. GHG impacts of off-farm feed production, see Fig. 1). Each lactation starts with a cow (or a heifer) giving birth to a calf. The farm-specific first calving age (FCA) and average number of lactations (ANL) per cow was thus used to calculate the number of replacement calves and heifers necessary to maintain a stable herd size. Milk output was measured and standardised to fat- and protein-corrected milk (FPCM) with 4% fat and 3.3% true protein content (IDF, 2015). All cows were assumed to be culled and considered as meat output at the end of their productive life span with farm-specific adult live weight (kg) per cow (LWC). Surplus calves (not required for replacement) were considered as beef output (kg) with a birth weight of the calf (BWC) computed according to NRC (2001) as:

$$BWC = LWC * 0.0675 \quad (1)$$

The fattening of surplus calves for beef production and the associated emissions were excluded.

As Assuming 5% losses of new born calves, the meat output (kg live weight) per cow and lactation was computed as follows:

$$Meat\ output = LWC/ANL + BWC * 0.95 * (1 - 1/ANL) \quad (2)$$

2.2. Net energy requirement for lactation and growth

In the standard biophysical allocation method recommended by IDF (2015), the allocation factor associated to milk (AF_{milk_std}) is derived linearly from the BMR (based on Thoma et al. (2013)):

$$AF_{milk\_std} = 1 - 6.04 * BMR \quad (3)$$

Our biophysical allocation method follows the idea of allocating between milk and meat according to the respective net energy requirement for milk and body mass growth. The allocation factor for milk (AF_{milk}) is thus the ratio of the net energy requirement for the annual milk production (MJ $NE_{lactation}$) and the annual net energy requirement for milk production plus growth (MJ $NE_{lactation}$ + MJ NE_{growth}) as proposed by Nemecek and Thoma (2020):

$$AF_{milk} = NE_{lactation} / (NE_{lactation} + NE_{growth}) \quad (4)$$

AF_{milk} follows by definition a hyperbolic distribution and is thus assumed to be applicable for any natural number for $NE_{lactation}$ and NE_{growth}. Net energy requirement for the production of one kg FPCM was set to 3.17 MJ (IDF, 2015). Net energy requirement (MJ) for the annual milk production of one cow ($NE_{lactation}$) was set to:

$$NE_{lactation} = 3.17 * MP \quad (5)$$

where **MP** is the mean annual milk performance (kg FPCM/year) per cow.

The energy requirement for growth was derived from the body mass growth required to replace a cow depending on the ANL. For instance, to replace a cow with an ANL of 3, one third of a cow needs to be raised for

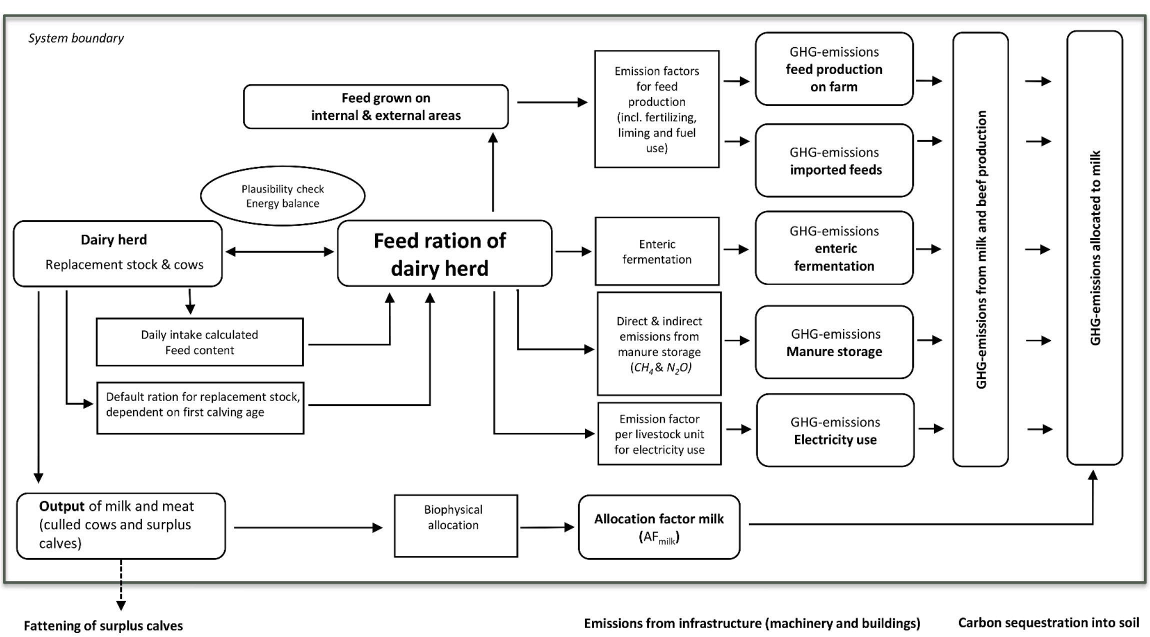

Fig. 1. System boundary and flow chart applied for greenhouse gas emission modelling, adapted from Köke et al. (2021).

every lactation. Computations for growth applied here are based mainly on NRC (2001) recommendations, which refer to megacalories of metabolizable energy (Mcal ME). Conversion factors for MJ NE are 1 Mcal = 4.184 MJ and NE = 0.64 ME, respectively. The IPCC (2019) thus recommends the following equation to compute net energy requirements for growth:

$$NE_{g\_day} = 22.02 * (BW/(C * MW))^{0.75} * WG^{1.097} \tag{6}$$

where $\mathbf{NE_{g\_day}}$ is the net energy needed for growth (MJ/day), **BW** is the average live body weight of the animals in the population (kg), **C** is a coefficient for sex (here set to 0.8 as all replacement cows are female), **MW** is the mature body weight of an adult animal in moderate body condition (kg) and **WG** is the average weight gain of the animals in the population (kg/day).

Energy requirements for the rearing replacement stock were subdivided into three distinct growth stages: birth until first breeding (NE_{g_fb}), first breeding until first calving (NE_{g_fc}) and the body weight gain as an adult animal after first calving (NE_{g_mat}). WG and BW were computed farm specifically for each growth stage. The net energy required for gestation (NE_{g_ges}) was added independently of whether the animal was raised or culled, as the body mass was considered as meat output either way to compute total net energy required for growth (NE_{growth}):

$$NE_{growth} = \left(NE_{g\_fb} + NE_{g\_fc} + NE_{g\_mat}\right)/ANL + NE_{g\_ges} \tag{7}$$

According to the NRC (2001) recommendations, the first breeding weight (FBW) and first calving weight (FCW) were set to 55% and 82% of LWC respectively. Further, cows were assumed to reach their adult body weight (LWC) after two years (730 days). First breeding age (FBA) was assumed to be 280 days lower than the FCA. Net energy requirements (MJ) for the different rearing stages were thus computed applying equation (6) to:

$$NE_{g\_fb} = 10.78 * (0.4825 * LWC/(FCA - 280))^{1.097} * (FCA - 280) \tag{8}$$

$$NE_{g\_fc} = 5488 * (0.27 * LWC/280)^{1.097} \tag{9}$$

$$NE_{g\_mat} = 17705 * (0.18 * LWC/730)^{1.097} \tag{10}$$

where **LWC** is the live weight of the cow (kg) and **FCA** is the first calving age (days).

Assuming a standard pregnancy duration of 280 days and a linear increase in energy requirement during gestation, MJ NE_{g_ges} was derived from NRC (2001) and computed as follows:

$$NE_{g\_ges} = 27.24 * BWC = 1.839 * LWC \tag{11}$$

Including equations (8-11) in (7) leads to:

$$\begin{aligned} NE_{growth} &= \left(10.78 * (0.4825 * LWC/(FCA - 280))^{1.097} * (FCA - 280) + 5488 * (0.27 * LWC/280)^{1.097} + 17705 * (0.18 * LWC/730)^{1.097}\right)/ANL + 1.839 * LWC \\ &= \left(10.78 * (0.4825 * LWC/(FCA - 280))^{1.097} * (FCA - 280) + 4.648 * LWC^{1.097}\right)/ANL + 1.839 * LWC \end{aligned} \tag{12}$$

where **LWC** is the mean live weight of an adult cow (kg), **FCA** is the mean first calving age (days) and **ANL** is the average number of lactations per cow.

By dividing NE_{growth} by the mass of meat output (kg LW), the net energy (MJ) necessary for the growth of one kg LW ($NE_{growth/lw}$) was computed specifically per farm:

$$NE_{growth/lw} = NE_{growth}/beef\ output \tag{13}$$

2.3. Modelling emissions from increased longevity

To assess the impact of increased longevity of cows on the fraction of emissions associated with milk, the greenhouse gas (GHG) emissions of 46 dairy farms based in the region of Bern, Switzerland, were computed. The farms registered themselves to participate in the research project 'climate friendly and resource efficient milk production' (KLIR, see Köke et al. (2021)) based on their willingness to adapt management practices to reduce GHG emissions. They were selected based on their geographic location and reflect a range of mainly grass-based Swiss dairy production systems in the lowlands but also in mountainous regions (Table 1). In addition to farms specializing in milk production and thus using dairy breeds only, farms using dual-purpose breeds were also investigated. Farm data was collected based on mandatory farm documentations during farm visits in 2018. The mechanistic KLIR emissions (Fig. 1) model as described by Köke et al. (2021) was used to model GHG emissions. In brief:

- The feed ration of cows was collected on farm and cross-checked with an energy balance at herd level. Feed contents and digestibility were taken from the Swiss feed database (Agroscope, 2016).
- Dry matter (DM) intakes of primi- and multiparous cows were calculated according to Swiss feed recommendations depending on milk performance and live weight (Jans et al., 2015).
- Direct and indirect emissions (CO_2, CH_4 and N_2O) from enteric fermentation, feed production (including fertilizing, liming and fuel use on both internal and external areas), manure storage and electricity use on farm were modelled.
- Emission factors for feed production were calculated in the Ecoinvent V3.6 database (Wernet et al., 2016), using the 'allocation, recycled content – unit' method.
- Methane emissions from enteric fermentation were calculated according to Liu et al. (2017):

$$D_m = 40.69 - 43.84 * ED - 4.87 * EIL + 6.368 * ED * EIL \tag{14}$$

where $\mathbf{D_m}$ is the percentage of digestible energy intake (MJ) converted to CH_4, **ED** is the energy digestibility of feed (fraction) and **EIL** is the energy intake level (dimensionless index). As both farm-specific dairy rations and information concerning the feed content and digestibility were available, this approach was considered to be more precise than the IPCC (2019) tier 2 approach.

- Emissions from manure storage were computed applying methods and coefficients from IPCC (2019) and refinements from FOEN (2020) for cool and dry climate conditions.
- The functional unit was 1 kg FPCM with 4% fat and 3.3% true protein content at the farm gate.
- CO_2-equivalents (eq.) were calculated with the Global Warming Potential conversion factors for a 100-year horizon (GWP100): 1 kg CH_4 = 25 kg CO_2-eq and 1 kg N_2O = 298 kg CO_2-eq (IPCC, 2007).

Table 2
Mean and standard deviation () of the international farm dataset (n = 350) used for testing the developed biophysical allocation approach.

Item/country	AR	BR	CH	CL	CN	CO	DM	EC	ES	MO	PE	PK	TH	ZA
Number of farms	15	33	95	12	12	28	12	14	85	10	8	12	3	11
Number of archetypes[1]	4	7	95[2]	2	4	9	4	4	3	3	2	3	1	4
Live weight cow (kg)	540 (108)	526 (69)	654 (52)	532 (42)	635 (36)	459 (67)	321 (57)	502 (34)	573 (64)	635 (58)	480 (145)	480 (74)	450 (0)	412 (27)
First calving age (days)[1]	780 (42)	886 (40)	837 (66)	908 (0)	748 (14)	1208 (186)	1104 (28)	890 (16)	789 (11)	756 (0)	854 (31)	915 (152)	847 (0)	811 (18)
Average number of lactations[1]	3.8 (1.0)	3.3 (0.5)	3.6 (1.1)	3.3 (0.5)	2.6 (0.3)	4.7 (1.4)	3.0 (0)	6.0 (0)	2.8 (0.6)	5.5 (1.4)	4.1 (0.5)	5.5 (1.2)	2.1 (0)	4.1 (0.3)
Milk performance (kg FPCM[3]/ cow/year)	7415 (2131)	5577 (2362)	7293 (1445)	6547 (2138)	8816 (2047)	2436 (2042)	2225 (710)	4541 (1515)	9314 (1967)	5699 (2135)	3927 (2891)	6411 (3274)	3714 (747)	4771 (1825)

AR=Argentina, BR=Brazil, CH=Switzerland, CL=Chile, CN=China, CO=Colombia, DM=Dominican Republic, EC=Ecuador, ES=Spain, MO=Morocco, PE=Peru, PK=Pakistan, TH=Thailand, ZA=South Africa

[1] First calving age and average number of lactations determined by archetype.

[2] No archetypes. All data collected individually.

[3] Fat- and protein-corrected milk

2.4. International farm data with large range of beef-to-milk ratio

To assess the impact of the biophysical allocation methods on farms with widely varying BMR, an unbalanced international farm dataset from Nestlé was used. A total of 350 farms in 14 markets worldwide were assessed. The selection of the markets and farms depended on the availability of input data. Average annual milk performance (kg FPCM) and the mean LWC (kg) of cows were collected on farm and used to calculate BMR. The FCA and ANL were estimated for groups of similar farms (see Table 2). These so-called archetypes are based on country specific parameters such as the type of manure management, confined vs. grazing systems and production intensity. A broad range of production systems were encountered, characterised by the large range for LWC (200 - 780 kg), FCA (696 -1 452 days), ANL (1.4 – 7.0) and milk performance (406 – 13 256 kg FPCM/cow/year)

2.5. Statistical analysis

The impacts of increasing the ANL by one additional lactation on total and rearing GHG emissions per cow, meat output, BMR as well as GHG emission intensity before and after allocation (applying the standard as well as the as the developed allocation method) were tested using the 'stats' package in R studio version 4.0.4 (R Core Team, 2021). Normality was tested applying the Shapiro-Wilk test and homoskedasticity using Bartlett and Levene tests, applying a significance level of 0.05. If data was non-normally distributed, the non-parametric rank sum test of Kruskal-Wallis was used.

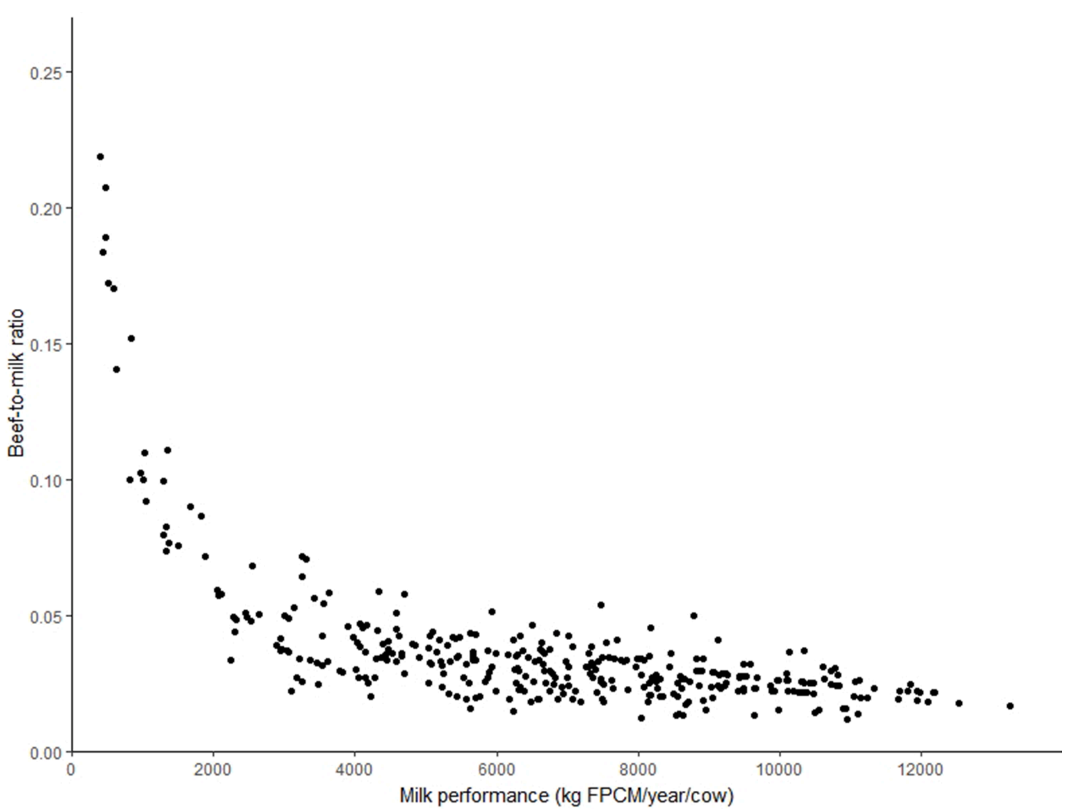

Fig. 2. Relationship between milk performance (fat- and protein-corrected milk) and beef-to-milk output ratio (BMR (kg LW/kg FPCM)) for the international farm dataset (n=350).

3. Results

3.1. Impacts of the allocation method for large beef-to-milk ratios

Observed BMR varied between 0.017 and 0.219 kg LW/kg FPCM (mean and standard deviation, 0.037 ± 0.027 kg LW/kg FPCM) and clearly correlated with the milk-performance level per cow (Fig. 2). Assuming the system boundary described in section 2.1, the BMR is further affected by LWC, FCA and ANL, which explains the variation at a given milk-performance level. Large BMR (>0.10 kg LW/kg FPCM) were rare and occurred only on farms with milk-performance levels below 1 000 kg FPCM/year/cow in smallholder production systems in evolving economies. However, BMR larger than 0.03 kg LW/kg FPCM frequently occurred even on farms with milk-performance levels larger than 10 000 kg FPCM/year/cow.

As for the BMR, the net energy required for the growth of one kg LW of beef output ($NE_{growth/lw}$) is an imputed value that depends on LWC, FCA and ANL. For the 14 markets assessed, it varied between 15.5 and 19.3 MJ with 90% of the values between 16.3 and 18.4 MJ and a median of 17.1 MJ (Fig. 3). Due to market-specific agricultural production properties, such as specifically low or high LWC and/or ANL, the farms in some markets group at the upper or lower boundary.

No BMR lower than 0.017 kg LW/kg FPCM was observed in the present study. Differences between AF_{milk_std} and AF_{milk} were small for low BMR. For BMR up to 0.025 kg LW/kg FPCM, the maximal deviation between the two methods was 0.035, for BMR up to 0.03 kg LW/kg FPCM it was 0.047. Differences became larger the higher the BMR was. The application of the standard biophysical allocation method on farms with BMR higher than 0.16 kg LW/kg FPCM led to negative values for AF_{milk_std} (Fig. 4). Although these cases were not very frequent, they did occur in the sample. The developed method led to positive values for AF_{milk} for farm cases with BMR larger than 0.16 kg LW/kg FPCM. In relation to BMR, AF_{milk} follows a hyperbolic course, and the slope was generally flatter than for AF_{milk_std}. Shifts in BMR (e.g. induced by changes in agricultural practices such as increased longevity of cows) thus have larger impacts on AF_{milk_std} than on AF_{milk}. Further, AF_{milk} is affected less the larger the BMR is at the starting point. The AF_{milk} computed using this $NE_{growth/lw}$ default value varied only slightly from the AF_{milk} using the farm-specifically calculated NE_{growth} (Fig. 5) with a mean difference of -0.0005, a standard deviation of 0.006 and a maximum difference of -0.021.

3.2. Impacts of increased longevity on beef-to-milk ratio and emissions allocated to milk

Computed for the Swiss farm dataset, GHG emissions were mainly caused by enteric fermentation (mean ± SD; 4 357 ± 3 057 kg CO_2-eq/cow/year), followed by emissions from feed production (on- and off-farm including fertilising, liming and fuel combustion 1 820 ± 1 366 kg CO_2-eq/cow/year) and manure storage (1 601 ± 1 145 kg CO_2-eq/cow/year). Emissions from electricity consumption on farm were minor (95 ± 169 kg CO_2-eq/cow/year). Total annual GHG emissions ranged from 5 225 to 9 017 kg CO_2-eq per cow (including emissions from rearing replacement stock, Table 3). Rearing emissions contributed 24.1% to total herd emissions. Before allocation, emission intensity varied largely (0.724 - 1.29 kg CO_2-eq/kg FPCM), but so did the amount of meat output (171 – 441 kg/cow/year). BMR ranged from 0.024 to 0.059 kg LW/kg FPCM. Applying the standard allocation approach, the allocation factor for milk (AF_{milk_std}) varied over 0.211 between the maximum and the minimum value, which reduced the range of allocated emission intensity (0.598 – 0.855 kg CO_2-eq/kg FPCM). Applying the developed allocation method, AF_{milk} was on average 0.059 higher than with the standard biophysical allocation method and varied less (0.126), resulting in an emission intensity that was higher by 0.065 kg CO_2-eq/kg FPCM. While the minimum of the allocated emission intensity was only slightly affected by the choice of the allocation method (+0.029 kg CO_2-eq/kg FPCM kg), the maximum was much more affected (+0.119 kg CO_2-eq/kg FPCM).

When increasing the ANL, less replacement stock must be raised. For instance, for an ANL of three, 0.33 heifers need to be raised per cow and

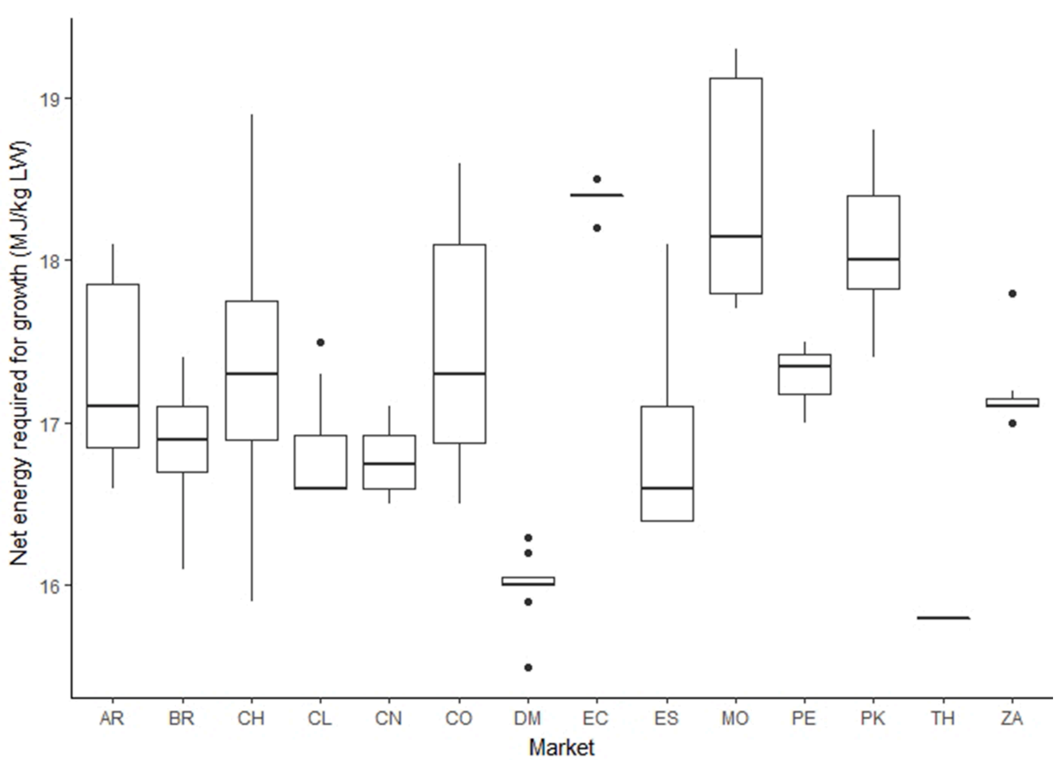

Fig. 3. Net energy required for the growth of one kg LW (live weight) of meat output for the 14 markets examined.AR=Argentina, BR=Brazil, CH=Switzerland, CL=Chile, CN=China, CO= Colombia, DM=Dominican Republic, EC=Ecuador, ES=Spain, MO= Morocco, PE=Peru, PK=Pakistan, TH=Thailand, ZA=South Africa

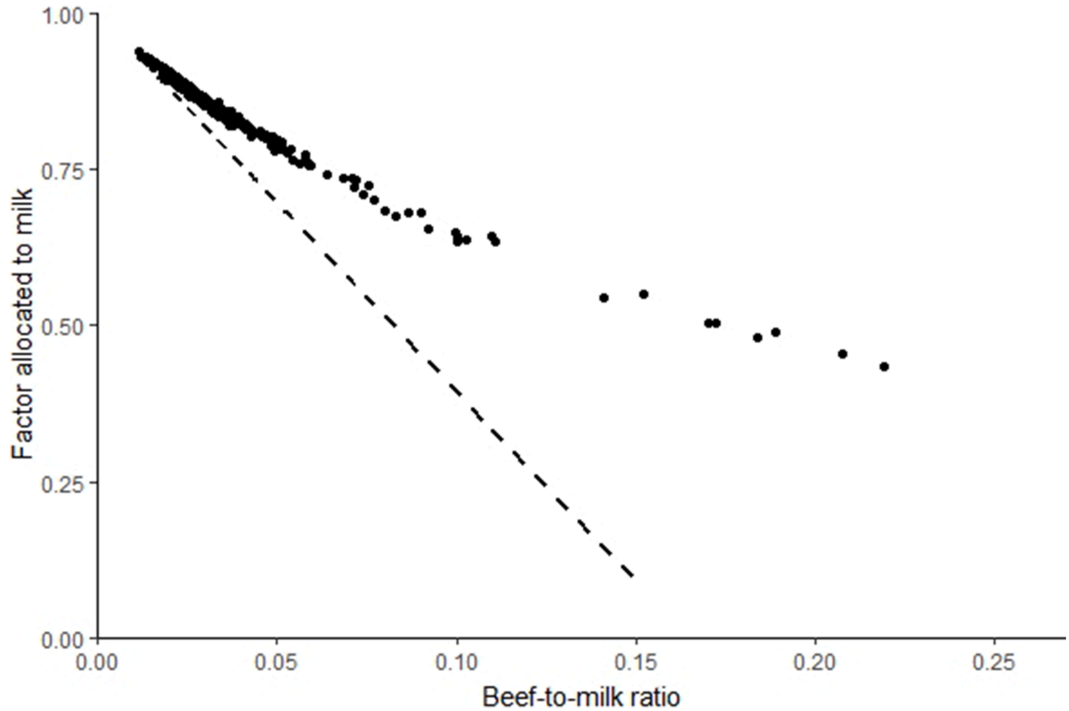

Fig. 4. Factor determined to allocate environmental impacts to milk according to the standard approach (AFmilk_std according to Thoma et al. (2013), dashed line) and the developed biophysical approach (AFmilk as developed in this study, dots) in relation to the beef-milk ratio (kg LW/kg FPCM)

lactation, while for an ANL of four, only 0.25 heifers are required. The proportional contribution of emission sources (enteric fermentation, manure storage, feed production, electricity use) remained stable. But the additional lactation reduced annual rearing emissions by 444 kg CO_2-eq/cow/year and thus affected total emissions per cow in the same range (scenario L4 in Table 3). Maximum rearing emissions per cow declined much more than mean and minimum emissions, the proportion of rearing emissions on total herd emissions was reduced through the additional lactation by 5.2% (Table 3). The culling of fewer cows resulted not only in fewer emissions through the rearing of replacement stock but generated also less meat output (-61 kg/cow/year on average and -146 kg/cow/year as the maximum) and decreased BMR (-0.09 kg LW/kg FPCM on average). Applying the standard allocation method, AF_{milk_std} was increased by 0.050 on average, while the minimum (deriving from the farm with the largest beef-to-milk ratio) increased by 0.069 (Table 3). The maximum AF_{milk_std} was affected much less, as the minimum BMR was only slightly reduced. As AF_{milk_std} increased strongly, allocated emissions were reduced neither for total emissions (+7 kg CO_2-eq/cow/year, n.s.) nor for emission intensity (+ 0.002 kg CO_2-eq/kg FPCM, n.s.). The considerable increase in AF_{milk_std} because of the only slight decrease in the BMR thus outweighed the emissions avoided by rearing fewer heifers (and longer-living cows). Applying the developed allocation method, AF_{milk} increased with an additional lactation per cow only by 0.028. After allocation to milk, both total emissions (-161 kg CO_2-eq/cow/year) and emission intensity (-0.022 kg CO_2-eq/kg FPCM) were reduced on average, although the difference was not significant. Applying the developed allocation method, the avoided emissions by rearing fewer heifers thus outweighed the effect of less beef output on average, but the reduction of one additional lactation was not significant.

4. Discussion

4.1. Biophysical allocation for large beef-to-milk ratios

In both datasets there is a relevant number of farms with BMR higher than 0.03 kg LW/kg FPCM, even on rather high-performing farms, while the standard biophysical allocation method developed by Thoma et al. (2013) relies on a US dataset with BMR mainly lower than 0.03 kg LW/kg FPCM. These differences are likely to be caused by the methodology to assess beef outputs as well as properties of the underlying dataset. It may firstly be explained by the fact that the system boundary was set differently. Here, depending on the replacement rate, only replacement animals to maintain a stable herd size were included and surplus calves counted as beef output after birth, while Thoma et al. (2013) considered all on-farm animals. Secondly, as Nemecek and Thoma (2020) have pointed out before, the standard biophysical allocation method does not count these sold surplus heifers as beef output, as the system boundary here was set to the farm gate while in Thoma et al. (2013) it was set to the whole dairy sector. Thirdly, Thoma et al. (2013) counted only cows registered as culled which may cause lower amounts of beef output if sold cows are not actuallyregistered as culled, while here the number of culled cows was computed depending on the replacement rate. We chose this approach because in the international dataset there was no reliable information about the actual number of culled cows. Further, there are markets that do not disclose replaced cows as culled, be it because the culling of cows conflicts with religious beliefs or due to low market prices. While the fate of these cows may be unknown, we assumed that the majority is of economic value and thus counted it as meat output. The fourth reason for largely varying BMR may be the fact that in our study a large variety of production systems was assessed, some of which were actually intended to increase the co-product meat or did not even consider milk to be the main output product.

For low BMR, our biophysical allocation approach does not generate allocation factors for milk that differ largely from the standard allocation approach. For BMR larger than 0.03 kg LW/kg FPCM, differences between the two methods become substantial. Although BMR larger than 0.16 kg LW/kg FPCM did not occur very frequently in this international dataset, allocation methods that are suitable for covering these extreme cases are necessary. A biophysical method that allocates emissions to milk and meat depending on the energy requirements for milk

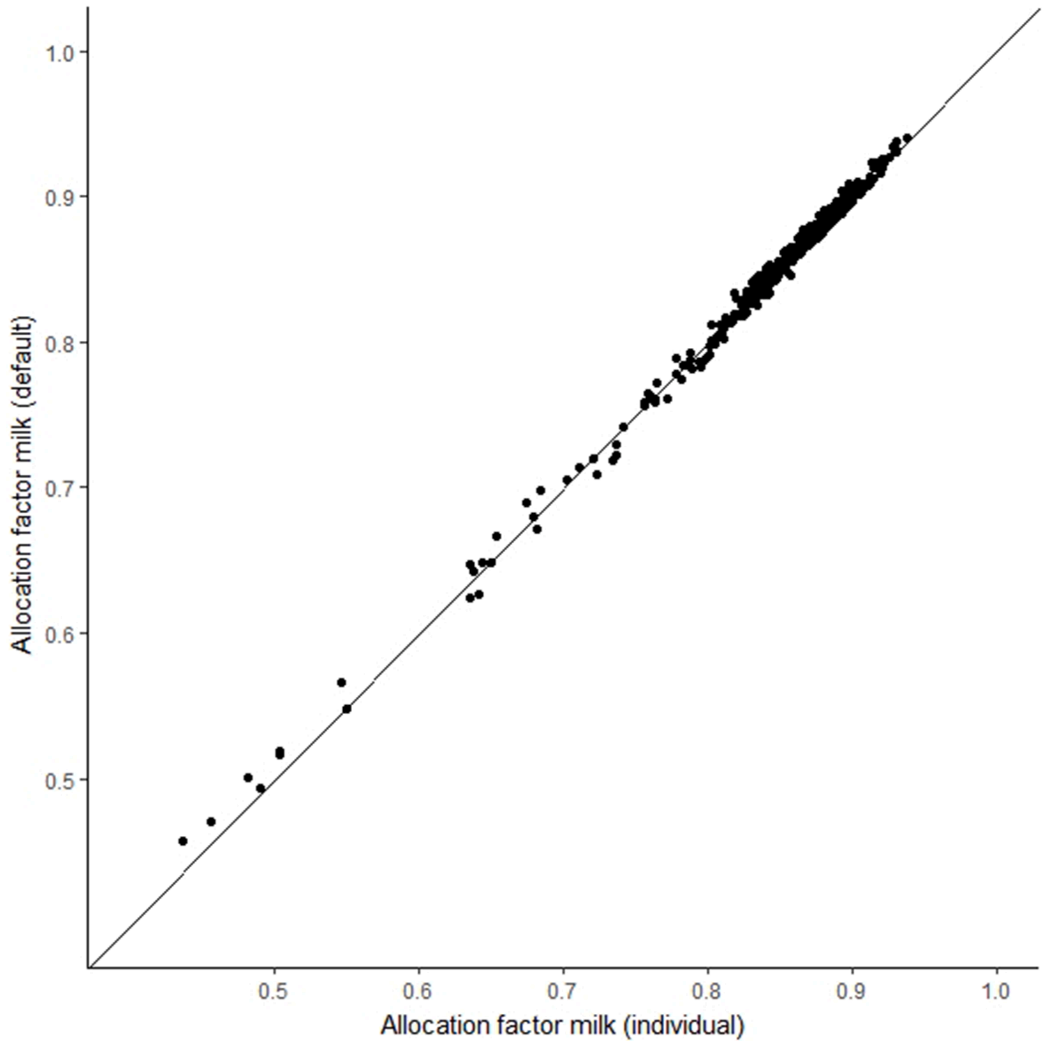

Fig. 5. Deviation between using the farm-specific (individual) and a default (17.1 MJ) value of net energy required for the growth of one kg beef output to determine the developed allocation factor that is associated with milk production (AFmilk). The solid line references equality line (x=y).

Table 3
Effect of an additional lactation (L4) compared to the average number of lactations per cow in the baseline (L3). Impacts on beef-to-milk ratio and accordingly modelled greenhouse gas emissions allocated to milk on 46 Swiss dairy farms.

	L3			L4					
	Mean	Min	Max	Mean	Min	Max	SEM	F-value[1]	p-value
Total emissions (kg CO_2-eq[4]/cow/year)	6751[a]	5225	9017	6337[b]	4885	8174	82.6	6.595	0.011
Rearing emissions (kg CO_2-eq/cow/year)	1643[a]	980	2984	1199[b]	810	1817	45.9	25.685[1]	<0.001
Rearing emissions/total emissions	0.241[a]	0.165	0.355	0.189[b]	0.140	0.288	0.0050	29.965[1]	<0.001
Total emission intensity (kg CO_2-eq/kg FPCM[5]) without allocation	0.951[a]	0.724	1.29	0.894[b]	0.686	1.18	0.012	6.226	0.014
Meat output (kg/cow/year)	268[a]	171	441	207[b]	148	295	6.0	27.619[1]	<0.001
Beef-to-milk ratio (kg LW/kg FPCM[5])	0.038[a]	0.024	0.059	0.029[b]	0.020	0.047	0.0008	33.032[1]	<0.001
Standard allocation method[2]									
Allocation factor milk ($AF_{milk\ std}$)	0.773[a]	0.644	0.855	0.823[b]	0.713	0.878	0.0048	33.032[1]	<0.001
Allocated emissions (kg CO_2-eq/cow/year)	5214[a]	3366	7015	5221[a]	3482	6892	69.4	0.002	0.960
Allocated emission intensity (kg CO_2-eq/kg FPCM)	0.731[a]	0.598	0.867	0.733[a]	0.594	0.878	0.0067	0.019	0.890
Developed allocation method[3]									
Allocation factor milk (AF_{milk})	0.832[a]	0.756	0.882	0.860[b]	0.788	0.895	0.0028	30.222[1]	<0.001
Allocated emissions (kg CO_2-eq/cow/year)	5615[a]	3952	7565	5454[a]	3849	7173	71.4	1.263	0.264
Allocated emission intensity (kg CO_2-eq/kg FPCM)	0.789[a]	0.627	0.986	0.767[a]	0.611	0.941	0.0079	1.93	0.168

[1] Test statistics as non-normally distributed: chi-squared (χ^2) and p-value according Kruskal-Wallis rank sum test
[2] Standard biophysical allocation approach (IDF, 2015)
[3] Developed biophysical allocation approach as presented in this paper
[4] CO_2 equivalents
[5] Fat- and protein-corrected milk

production and growth, as proposed in this paper, complies with this necessity. This also applies for the simplified method, where the median of 17.1 MJ NE_{growth}/kg meat output (LW) is set as a default to compute the net energy used for growth. Although in life cycle assessment generally all required data should be available to calculate net energy required for growth (see NE_{growth} in equation 12) as deduced in this study, using the default value of 17.1 MJ NE_{growth}/kg meat output (LW) is recommended for a straightforward determination of the allocation factor associated to milk.

4.2. Impact of increased longevity on the allocation of greenhouse gas emissions

GHG emissions computed by the KLIR model for the 46 Swiss dairy farms (before allocation 0.951 CO_2-eq/kg FPCM on average) were at the lower boundary of comparable studies. To avoid bias through the obviously relevant choice of allocation methods (Rice et al., 2017), we compared our results with unallocated emission intensity of similar whole-farm emission models without carbon sequestration (applying the same GWP conversion factors). O'Brien et al. (2014) for instance found 0.914 kg CO_2-eq/kg energy corrected milk (ECM) for top performing grass-based Irish dairy farms, while Kristensen et al. (2011) reported 1.20 CO_2-eq/kg FPCM for conventional dairy farms in Denmark and van Middelaar et al. (2014) 0.910 CO_2-eq/kg FPCM for intensive Dutch farms. As this paper mainly focuses on the effect of longer-living cows on emissions from replacement stock und thus on overall emission intensity, the impacts of mitigation measures are likely to be valid irrespective of the underlying emission model.

Measures that reduce emissions from non-productive animals are promising strategies to mitigate negative environmental impacts of dairy production (Hristov et al., 2013). Knapp et al. (2014) estimated an approximately 6% reduction in the contribution of replacement stock to overall methane emissions from enteric fermentation of the dairy herd by reducing the culling rate from 0.35 to 0.25. Although methane is the most important source of GHG emissions in ruminant production systems (Gerber et al., 2013), other relevant GHG sources (N_2O and CO_2 from feed production, manure handling etc., see Fig. 1) occur over the complete dairy production cycle. As observed here, reducing replacement stock cuts all emissions proportionally. Consequently, it can be assumed that the reduction potential through further GHG sources is equivalent to that estimated for enteric fermentation. The 5.2% reduction in rearing emissions relative to total GHG emissions when reducing the replacement rate from 0.33 to 0.25 which we observed (Table 3) is thus in line with the findings by Knapp et al. (2014). Notable reduction in GHG emissions through increasing the productive lifespan of cows has previously been reported (van Middelaar et al., 2014; Bell et al., 2015). These findings are, however, not directly comparable to our results, as impacts vary largely depending on the defined system boundary and the allocation approach. Further, the actual effect of longer-living cows on GHG emissions needs to be assessed with respect to changes in meat output as well as the allocation of the remaining emissions to milk and meat (Flysjö et al., 2012; Zehetmeier et al., 2014; Vellinga and de Vries, 2018). Increasing longevity reduces not only emissions from rearing replacement stock but also meat output, as fewer cows are culled, as also shown by Vellinga and de Vries (2018). The quantification of lacking meat depends on the system boundary, live weight of the cows as well as the first calving age. However, it may also be influenced by the baseline ANL, which could be explained by decreasing marginal utility, as an additional lactation has a much greater effect if the baseline is low and vice versa. For instance, the minimum ANL of the farms examined is 1.4 (Table 1). An additional lactation is a 171% increase, which reduced the number of replacement stock from 0.71 to 0.36 and which essentially decreased rearing emissions, but, as a consequence, also decreased meat output by 146 kg/cow/year. BMR decreases with lower meat output, the extent of which depends on the milk-performance level of the cows. For instance, 100 kg less meat output for a cow performing at 1 000 or 10 000 kg FPCM per lactation decreases BMR by 0.1 or 0.01 kg LW/kg FPCM respectively. The BMR in high-performing dairy systems is consequently less influenced by changing amounts of beef output, while the effect is much more obvious in low-performing dairy systems. Applying the standard biophysical allocation method (IDF, 2015), shifts in BMR caused relevant shifts in AF_{milks_std}. This eventually even over-compensated the emission-reduction effect induced by increasing the productive lifespan (e.g. longer-living cows), resulting in increased emissions allocated to milk when the impacts of replacement stock decreased. Our biophysical allocation approach, which derives AF_{milk} as a ratio between the net energy requirement for milk and the total requirement for milk and meat production, is less sensitive to shifts in BMR, especially for low-performing dairy farms. It is thus suited to cover impacts of emission reduction measures that affect BMR. Nonetheless, reduction in GHG emissions from an additional lactation was only modest. From an energy flow perspective that is stringent, as a part of the energy used for rearing replacement stock is not 'lost' but 'retained' in the body of the (producing) cow and will finally – when the cow is culled – be considered an output of the milk production system. Clearly, increasing the longevity of cows does not essentially reduce GHG emissions if biophysical allocation is applied. It may, however, be of economic interest as the rearing of replacement stock causes considerable costs (Liang and Cabrera, 2015) and longer-living cows are associated with productivity gains on dairy farms (Ali, 2021).

4.3. Properties of the chosen system boundary and allocation approach

According to Berry (2021), meat from culled cows and fattened surplus calves contributes from around 20% in the US to almost 90% in other markets. The systematic insemination of dairy cows with beef bulls and the use of sexed semen may even increase beef output from dairy systems in the future. By setting the system boundary to the farm gate – as we did in this study - the intense interdependence of milk and beef production is not fully reflected. As emissions from the fattening of surplus calves were not included, the faster weight gain of dual-purpose or beef-cross dairy calves is not fully recognised (by the BWC). If the fattening of surplus calves were to be included in an assessment method, system boundaries would need to be drawn beyond the physical farm. This may be difficult to communicate when assessing individual farms, as relevant assumptions and processes are not influenceable by the dairy farm itself. The fattening, for instance, often does not take place on farm, but the assumed fattening system of surplus calves largely affects the assessment outcomes, as there is a large range of GHG emission intensity coefficients (Crosson et al., 2011; de Vries et al., 2015; Vellinga and de Vries, 2018) and interaction with the breed type (dairy, beef, crossed) must be assumed.

Allocating environmental impacts according to economic instead of biophysical properties could cover the larger fattening potential (increased weight gain) of certain breeds, as this is generally reflected in higher market prices. Mackenzie et al. (2017) thus claim economic allocation to be at least coequal and question the causality of the biophysical allocation approach according to the feed energy use. Nonetheless, the economic allocation of environmental impacts between milk and meat cannot be considered a promising internationally valid standard approach, as differences between milk and meat prices vary largely between markets. Emissions associated with milk would thus be strongly dependent on the market-specific price level for milk and livestock and, as market prices are very volatile, subjected to constant fluctuation.

Assuming constant milk and meat consumption, decreasing meat outputs from dairy systems are likely to be replaced by meat from beef systems. The environmental impacts of beef systems are, however, much higher (de Vries et al., 2015) and compensating lacking meat output from dairy systems may generate larger total emissions (Zehetmeier et al., 2012). To fully account for these compensation effects, instead of allocating emissions to milk and meat, system expansion as proposed by Cederberg and Stadig (2003) would be required. System expansion, however, demands a broader perspective and requires additional information and assumptions concerning the assessed processes (Thomassen et al., 2008). Consequently, uncertainty increases (O'Brien et al., 2014; Rice et al., 2017) and makes the application of system expansion inappropriate as a standard approach to avoid allocation issues in multi-output agricultural processes such as dairy production systems (Mackenzie et al., 2017).

5. Conclusion

While the applicability of the standard biophysical allocation approach is limited to very low BMR, the method presented in this paper is applicable to a great variety of dairy farms worldwide, with wide ranges of BMR including dual-purpose production systems. Increasing the longevity of dairy cows does not substantially reduce GHG emissions associated with milk production when applying the recommended standard biophysical allocation approach. Our method reflects changes in total GHG emissions from the rearing of replacement stock more adequately than the standard approach, as the fraction of emissions allocated to milk is less affected by shifts in the BMR. Although the complex interdependence of milk and meat outputs in dairy production systems is not fully represented by the choice of the farm and its upstream emissions as system boundary, we encourage the revision of the international standard for allocating environmental impacts to milk and meat in dairy production systems according to the method proposed in this paper.

CRediT authorship contribution statement

S. Ineichen: Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **U. Schenker:** Data curation, Methodology, Writing – review & editing. **T. Nemecek:** Methodology, Writing – review & editing. **B. Reidy:** Conceptualization, Methodology, Resources, Validation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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