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A biophysical approach to allocation of life cycle environmental burdens for fluid milk supply chain analysis

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ABSTRACT

Data from 536 United States of America dairy farms were used to test algorithms for milk to beef allocation. A wide range of rations was represented, from pasture-based to large confined animal operations. Variety in the animal classes sent to beef provided a very robust dataset. We report an empirical relationship for the causal allocation ratio (AR_c) based on detailed analysis of farm rations, to allocate whole farm emissions between milk and beef: $AR_c = 1-4.39 \cdot BMR$; with BMR defined as the kg beef sold per kg milk sold annually. USA dairy farm green house gas emissions allocated to milk using this approach was, on average, 91.5%, compared with economic (94.4%) and the protein-based (95%) allocation methods. We include an analysis of the allocation between fluid milk and excess cream at the processing plant. This analysis shows 19.8% of the post-farm (after allocation to beef) milk production burden allocated to the excess cream.

1. Introduction

Allocation of inputs and emissions from processes with multiple co-products is an important issue for product level life cycle allocation (LCA). The production of fluid milk requires numerous resource inputs and environmental outputs that contribute to environmental impacts. In the analysis of fluid milk, the assignment of burdens between the co-products milk and beef at the dairy farm gate is an important decision as it represents an 'accounting' choice that can drastically influence the reported study results. Another important allocation occurs at the processing stage where excess cream is removed from the fluid milk product stream.

LCA is intended to quantify the material and energy inputs and outputs associated with a specific system. In practice, industrial processes usually result in more than one valuable product: milk and beef are important considerations in this study. Here it is necessary to apply allocation of inventory and impacts from the LCA model. Allocation is the partitioning of the input and output flows of a system among the multiple system products. The ISO 14040/14044 (ISO, 2006) guidelines recommend a hierarchy of procedures for addressing this issue:

- If possible, avoid allocation by either dividing the unit processes so that inputs and outputs can be assigned to specific products OR expand the system to include the function of co-products.
- If dividing the unit processes and system expansion are not possible, the inputs and outputs of co-products should be divided based on process (causal) relationships between the co-products.
- If allocation cannot be accomplished based on physical (causal) relationships, then other relationships between the co-products should be used (e.g., economic value or mass).

The present allocation procedure specifically develops a consistent physical–causal approach for situations for which the available information is insufficient for use of system expansion.

For agriculture, large variations in allocation factors occur between commonly used allocations methods (Audsley et al., 1997). These can have large consequences on the reported impact of the studied product. In the specific case of the LCA of dairy production, allocation is required at different levels, feed, dairy farm, processing plants and the whole retail process (Basset-Mens, Ledgard, & Boyes, 2009; Cederberg & Mattsson, 2000; Cederberg & Stadig, 2003; Feitz, Lundie, Dennien, Morain, & Jones, 2007; IDF, 2010; Thoma et al., 2013). It is generally not practical to use a single allocation procedure across all the stages of the entire life cycle, therefore

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a combination of approaches is commonly employed; however, ISO does require that, for a given life cycle stage, the same allocation procedure be used. Specifically, for a meal:oil allocation, both soy meal and cottonseed meal should use the same allocation algorithm, for example, economic allocation. One of the most important and potentially most complicated allocation decisions is how to assign the cradle-to-farm gate environmental burdens between the co-products milk and beef (Eide, 2002) and between fluid milk and cream at the processing stage.

Cederberg and Flysjö (2004) used a 90% allocation of farm burdens to milk based on an economic revenue allocation. Thomassen, van Calker, Smits, Iepema, and de Boer (2008) also used economic allocation and reported approximately 90% of the farm burden allocated to milk produced in The Netherlands. One argument in favor of economic allocation is that it would account for the co-products of beef such as leather and bonemeal; however, these co-products result from activity outside of the dairy system, and accounting for allocation to these co-products is not necessary for this analysis. Further, this approach is only set as the fourth priority in the ISO hierarchy and suffers from the disadvantage of variation in the assigned environmental burdens associated with the relative value of each of the products in the marketplace over time.

In an LCA of Swedish milk production, Cederberg and Stadig (2003) present a comparison of allocation for Swedish milk production that range from an allocation to milk of 92% (economic) to 85% (biological) with a range of 60–100% for system expansion depending on the impact category. These results are similar to those reported in a later study by Flysjö, Cederberg, Henriksson, and Ledgard (2011). Thomassen, Dalgaard, Heijungs, and de Boer (2008) present a comparison of mass, economic and consequential (system expansion) approaches to allocation for Danish milk production. Their results were similar to those of Cederberg and Stadig (2003) in that the green house gas (GHG) emissions assigned to milk using system expansion were only approximately 60% of the GHG emissions derived from the other allocation methods. The authors' explanation for the lower allocation of farm gate burdens when system expansion is used was that the avoided production of beef in the beef industry provides a large credit to the dairy system. System expansion can be used effectively when there is a separate system for production of one of the co-products. In this situation, the life cycle impact of the separate process is subtracted from the impact of the system in consideration. This approach is difficult to apply to the milk and beef allocation problem in the USA since a separate good quality LCA for USA production of the substituted co-product is not available. In addition, for this approach, the impact allocated to milk becomes dependent on the type of beef production that is assumed to be displaced – a function of market elasticity and product fungibility – and is only valid for the specific substitution chosen.

Protein-based allocation is used by Gerber et al. (2010), partly representing the respective functionality of milk and beef. This is a more justifiable approach than a direct mass allocation, since there is no direct causal relationship between milk and beef masses and impacts. However, provision of protein in the diet is not the only function of milk and beef; calcium, potassium and fat also have important nutritional value.

Basset-Mens et al. (2009) used the biological approach of Cederberg and Stadig (2003) in a study of milk production in New Zealand, and reported that an economic allocation for New Zealand conditions would have resulted in the same 85:15 allocation. While Cederberg and Stadig (2003) outline the biological approach to allocation, they do not provide sufficient detail of the calculations to enable reproducing the approach and such calculations are relatively data intensive.

Based on the available literature, the allocation of cradle-to-farm-gate burdens to milk for attributional LCA ranges from 60% to approximately 95%. In this context, this paper explores whether a reliable method corresponding to the first and third priority from ISO, namely dividing the unit processes and physical causal relationship could be developed and applied to milk and beef allocation. In addition, we aimed to develop a simplified regression-based relationship to enable the application of this method on a large scale using readily available data.

In this paper, we describe in detail the development of a causal relationship for allocation of on-farm burdens to the co-products milk and beef. The method is tested on data from 536 USA dairy farms collected for the LCA of milk production and we develop a simplified version by performing a regression analysis of the allocation factors from these 536 farms. Allocation using this new causal approach is compared with both economic and protein content allocation methods in a scenario analysis.

2. Materials and methods

2.1. Milk–beef allocation

2.1.1. General principle

Fig. 1 depicts a simplified view of material (feed) and energy (nutritional) flows through a dairy operation. The concept of allocation between beef and milk based on the feed consumed by the animals that can be 'traced' to production of milk or beef satisfies the ISO standard for physical causality relationships between the co-products. Ideally, following the ISO standards, the system should be separated into distinct production lines in the inputs and the emissions associated with one or the other of the co-products would be directly assigned, thereby avoiding allocation for those specific impacts. Thus this approach would identity all activities on the farm that could be attributed solely to either beef or milk production and these would be directly allocated (i.e., not split between milk and beef). For example, electricity consumed in the milking parlor as well as refrigerant loss should be directly assigned to milk production. The unassigned environmental burdens at the farm gate, including all of the burdens associated with inputs of the fuel and electricity, enteric methane and manure management as well as animals' rations are allocated between the co-products beef and milk based on the causal relationship of feed consumed for production of both milk and beef. This approach can be conceptually extended with only minor modification to also account for animals sold from the dairy under study to another dairy: the allocation to this class of animal is also based on the feed energy required to grow the animal to its sale weight.

This allocation approach will provide the greatest level of resolution when applied at the individual farm level. At the individual farm level, where details of the animal weights and rations are known, it is possible to apply net energy (NE) conversion efficiencies for individual feed ingredients to retroactively estimate the amount of feed required to achieve the known sale weights.

NE refers to the energy per kg dry matter feed available for a specific metabolic activity in the animal; that is, NE_G (MJ kg^{-1}) and NE_L (MJ kg^{-1}) are the energy content of the feed available for growth or lactation, respectively. These calculations are performed for both bull calves and mature milking cows leaving the farm and thus the allocation fraction will be farm specific and account for differences in production efficiency. It is important to note that the allocation ratio (AR) derived in this manner is applied to the whole farm emissions except those that can be directly attributed to milk production.

Thus the general procedure for allocation of GHG emissions can be given by:

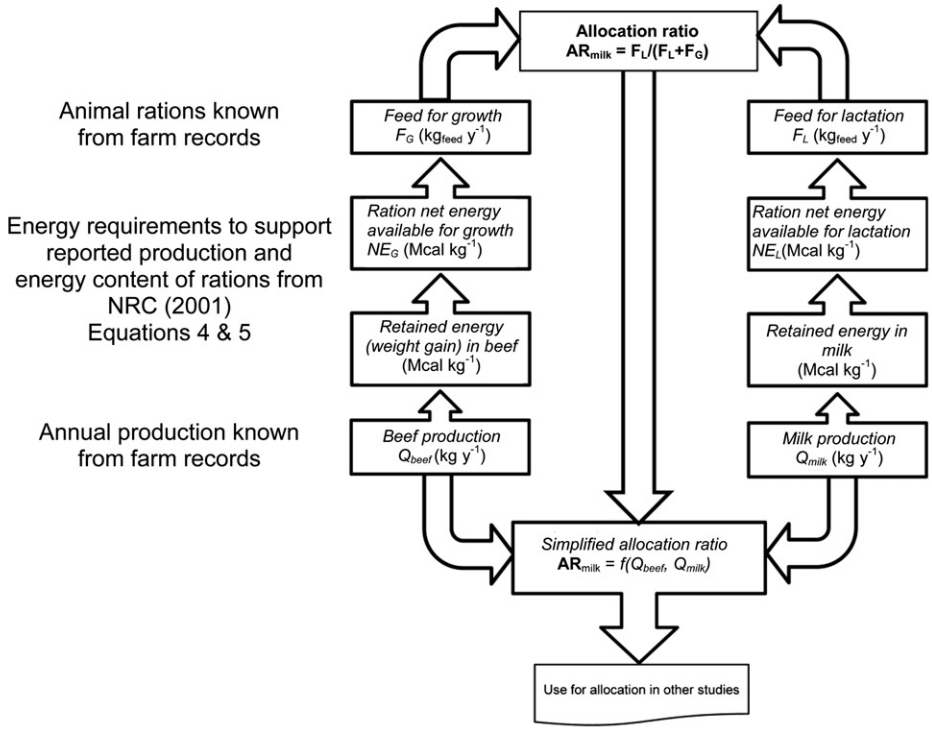

Fig. 1. Schematic showing inputs that are accounted in the causal allocation ratio calculation. Based on the procedure described in the text, the fraction of total farm feed that was consumed for production of the known farm output defines an allocation ratio that is used to distribute the cradle to farm gate impact between milk and beef.

$$\mathrm{GHG_{Milk}} = \mathrm{AR_{Milk}}\left[\sum_{\text{whole farm}} \mathrm{GHG} - \sum_{\text{milk only}} \mathrm{GHG}\right] + \sum_{\text{milk only}} \mathrm{GHG} \tag{1}$$

$$\mathrm{GHG_{Beef}} = (1 - \mathrm{AR_{Milk}})\left[\sum_{\text{whole farm}} \mathrm{GHG} - \sum_{\text{milk only}} \mathrm{GHG}\right] \tag{2}$$

$$\mathrm{AR_{Milk}} = \sum_{\text{lactating herd}} F_L \Big/ \left[\sum_{\text{lactating herd}} F_L + \sum_{\text{beef culls}} F_G\right] \tag{3}$$

where GHG_{milk} and GHG_{beef} are the cumulative GHG emissions (kg CO_2-equivalents) for the annual accounting period that are allocated to milk and beef, respectively. The AR, which defines the fraction of emissions that are assigned to milk, is calculated based on the annual feed necessary to supply the energy retained in the meat during growth (F_G, kg DMI yr^{-1}), where DMI is dry matter intake, and the feed to supply the energy retained in the milk during the lactating period (F_L, kg DMI yr^{-1}). Each summation in equations (1) and (2) is conducted on a cradle-to-farm-gate basis. Equations (1) and (2) are represented schematically in Fig. 1. The use of farm production information for calculation of the AR begins with the annual production of beef and milk (bottom row of boxes with upward arrows) that are combined, sequentially, with mathematical relationships for the energy retained for growth (left side) or milk production (right side), and published nutritional information to yield the respective share of the ration consumed for growth and for lactation leading to the AR for the studied system. The lighter arrows pointing down in the diagram represent the combination of data from 536 farms (Popp et al., 2013) into a simplified empirical predictor for AR based only on the beef and milk production; data that should be readily available. The gross energy content available from the feed is also used (see Fig. 2) for animal maintenance, mobility, enteric methane, and energy in manure that may be converted to methane or nitrous oxide, thus the GHG emissions for all those activities are shared between the milk product and beef products of the farm. It should be noted that any emissions associated with dead animal carcass management are also shared between milk and beef. Carcasses are not included in the calculation of feed consumed for growth as this mass of meat is not sold to the beef sector.

In the derivation for the AR, we have assumed that the dairy operation is in a pseudo-steady-state. This assumption is necessary because, while the accounting period for GHG emissions is one year, many of the animals that are culled into the beef production system will have been on the farm for longer than a single year, or, in the case of bull calves, for a period of time shorter than one year. Given a pseudo-steady-state operation, it is allowable to take the production and sales information from a one-year timeframe as representative of system operation. Specifically, if the rolling herd average population for each class of animals on the farm is approximately constant, then even as individual animals age during the year and change from one class to another, the cumulative feed used by that animal class will remain approximately constant. This allows us to estimate the AR by “back casting” from known production volumes of milk and sales to the beef sector to feed consumed for production of the milk and beef.

2.1.2. Net energy of ration for growth and lactation

As shown in equation (3), the AR is calculated as the ratio of the quantity of the farm ration that was consumed for milk production to the quantity consumed for milk and beef production. The physiological basis for this approach arises from the fact that, for each feed in the ration, the conversion efficiency for the production

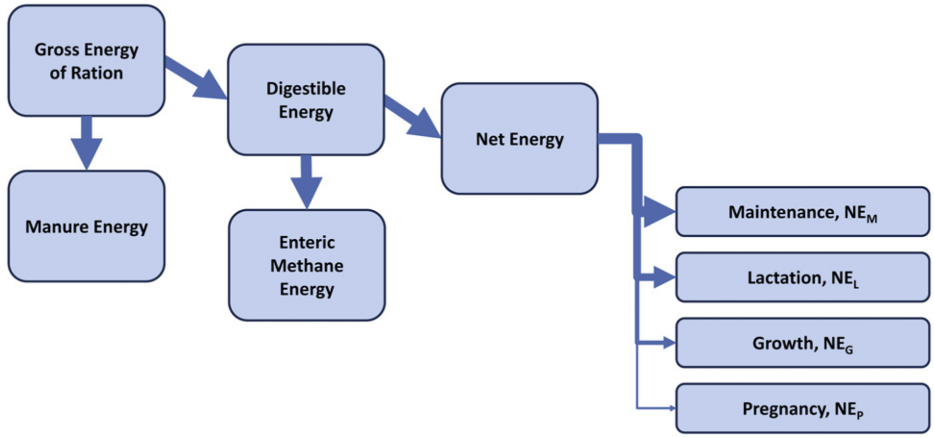

Fig. 2. Schematic showing the energy cascade for ruminants. The width of the arrows leading from the net energy box represent the precedence of metabolic activity in the animal.

of body mass in growing animals is different from the conversion efficiency of that feed for milk production. Dairy nutritionists account for this with the concepts of net energy for growth (NE_G) or lactation (NE_L).

NRC (2001) presents detailed information regarding the energy content of common feeds as well as mathematical models for estimating the amount of feed energy deposited as tissue and milk. In the nutrition tables, the data are reported as if the feed were used exclusively for one metabolic activity, and thus the summation of the net energies for growth and lactation is larger than the gross energy content of the feed. For our purposes, this is convenient because by combining it with the net energy retained in milk and meat, it allows separation of the back casting calculations for milk and beef and directly provides the mass of feed that must have been consumed to produce the reported products.

For the calculation of the AR, we need to determine the weighted average net energy content for the ration that is associated with each animal class, i, on the farm, shown schematically in Fig. 3 and mathematically below:

$$\overline{NE_G} = \frac{\sum_i F_i t_i NE_{Gi}}{\sum_i F_i t_i}; \quad \overline{NE_L} = \frac{\sum_i F_i t_i NE_{Li}}{\sum_i F_i t_i} \tag{4}$$

where F_i is the dry matter intake (kg day^{-1}) of feed i (e.g., corn silage) and t_i is the number of days per year that animals in that class consume the feed. It is not necessary to have daily feed consumption data to make an estimate of the weighted average net energy content of the rations. When less detailed data are available, average net energy content for forages and concentrates coupled with estimated annual consumption is sufficient to estimate NE_G and NE_L. Thus, in the case of a national scale evaluation of milk production, knowledge of the quantity of fat- and protein-corrected milk and beef produced coupled with the quantity of forage and concentrate consumed annually, is sufficient to estimate an AR.

The algorithm for calculation of the AR presented in this work is conceptually similar to the biological allocation presented by Cederberg and Stadig (2003) in which the feed energy deposited in the beef and milk products is estimated, and the ratio of the input feed energies is used to allocate the unattributed environmental burdens; however, the details of their calculations were not presented, and thus it remains unclear whether they differentiated between the different animal classes and growth stages.

In 2001, the National Research Council published "Nutrient Requirements for Dairy Cattle" that includes a detailed mathematical model for estimating feed and energy required for dairy operations (NRC, 2001). An earlier version of this model is used by the IPCC to model GHG emissions from the dairy sector. Equations are given for conceptus growth (net energy for pregnancy), growth of calves, open heifers (~3 months to first breeding, typically about 13 months old), and bred heifers through full adult weight. The

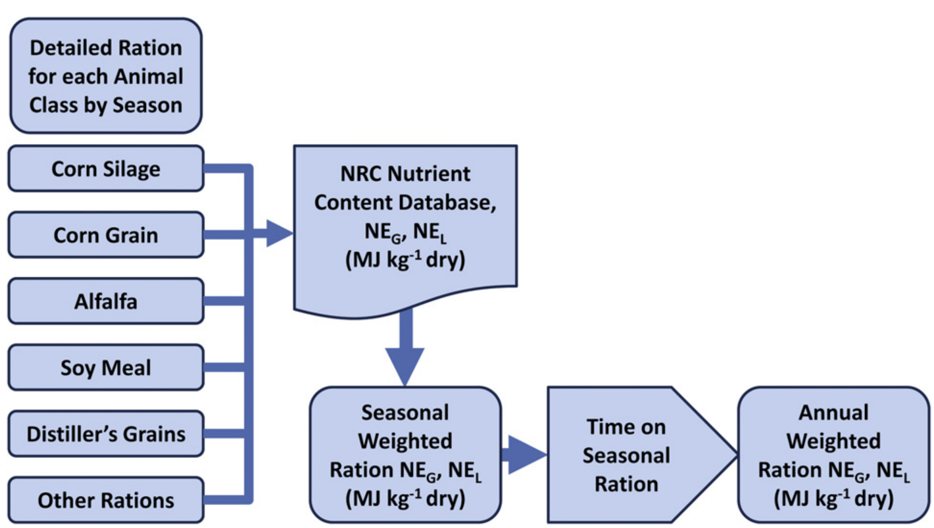

Fig. 3. Schematic showing the approach to estimate farm scale nutritional characteristics of the animal rations. This calculation is repeated for each animal class to provide an annual average ration based on reported feeds and nutrient content of each component.

equations give daily net energy requirements as a function of body weight and rate of weight gain, and thus must be integrated over the growth period to estimate the total net energy necessary for growth to the sale weight when the animal is transferred to the beef sector. In addition, estimation of the energy requirements for milk production is provided.

2.1.3. Feed requirement for lactation

The annual quantities of feed necessary to supply the energy for milk can be calculated as a function of the ratio of the net energy retained in the milk divided by the average of the NE of feeds for lactation ($\overline{\mathrm{NE}_L}$ MJ kg^{-1}):

$$\sum_{\text{lactating herd}} F_L = \frac{\sum_{\text{lactating herd}} \mathrm{RE}_L}{\overline{\mathrm{NE}_L}} = \frac{\mathrm{MP}\cdot(0.0929C_F + 0.05882C_P + 0.192)}{\overline{\mathrm{NE}_L}} \quad (5)$$

where RE_L is retained energy (MJ kg^{-1}) in the milk produced, MP is the annual milk production from the farm (kg yr^{-1}) multiplied by RE_L. RE_L is calculated as a function of the fat content (C_F, %) and of the protein content (C_P, %) of the milk produced. In the current study, these data were collected from a farm survey (Popp et al., 2013); regional or national average statistics may also be available for application of this approach in other regions.

Relations for estimating lactation energy requirement, or equivalently the feed energy deposited in the milk as a function of the fat and protein content, are given by NRC (2001, equations 2–16) where it is assumed that the lactose content is fixed at 4.85%, which is generally reasonable because of osmotic balancing requirements.

2.1.4. Feed requirement for growth

The annual quantities of feed necessary to supply the energy for growth and therefore production of beef is calculated as a function of the ratio of the net energy retained in the animal's body divided by the average of the NE of feeds for growth ($\overline{\mathrm{NE}_G}$ MJ kg^{-1}):

$$\sum_{\text{beef culls}} F_G = \sum_{\text{beef culls}} F_{\text{Gnew born}} + F_{\text{Gopen heifer}} + F_{\text{Gbred heifer}} + F_{\text{Gfirst calf heifer}} = \sum_{\text{beef culls}} \int_{\text{animal life}} \frac{RE_{Gk}(t)}{\overline{\mathrm{NE}_{Gk}}(t)} dt \quad (6)$$

where the integral is computed in a piecewise fashion over each animal's life prior to being culled to the beef sector:

$$\int_{\text{animal life}} \frac{\mathrm{RE}_{Gk}(t)}{\overline{\mathrm{NE}_{Gk}}(t)} dt = \int_{\text{conceptus}} \frac{\mathrm{RE}_{\text{Gconceptus}}(t)}{\overline{\mathrm{NE}_{\text{Gpregnancy}}}(t)} dt + \int_{\text{calf}} \frac{\mathrm{RE}_{\text{Gcalf}}(t)}{\overline{\mathrm{NE}_{\text{Gcalf}}}(t)} dt + \int_{\text{open heifer}} \frac{RE_{\text{Gopen heifer}}(t)}{\overline{NE_{\text{Gopen heifer}}}(t)} dt + \int_{\text{bred heifer}} \frac{\mathrm{RE}_{\text{Gbred heifer}}(t)}{\overline{\mathrm{NE}_{\text{Gbredheifer}}}(t)} dt + \int_{\text{first calf/mature}} \frac{\mathrm{RE}_{\text{Gmature}}(t)}{\overline{\mathrm{NE}_{\text{Gmature}}}(t)} dt \quad (7)$$

where F_G is the cumulative feed consumed (kg dry matter) that was deposited as body mass for animals culled from the dairy herd to the beef sector, $\mathrm{RE}_{Gk}(t)$ is the retained energy (MJ), or the energy deposited from the ration into the animal body mass for animal class k (conceptus, calf, open heifer, bred heifer and first calf/mature cow). $\mathrm{NE}_{Gk}(t)$ is written to denote that the ration may change over time for a specific animal class, but that it is certainly different for different animal classes. In the reported survey results there was typically very little difference in first calf heifer and multiparous lactating cow rations, hence the combined life stage in the last term of equation (7).

Estimation of the retained energy for each phase of an animal's life requires different mathematical relationships that are evaluated individually and provided in supporting information. The final equations for calculating the feed consumed for growth are:

$$F_{\text{Gnew born}} = \frac{(6.45\mathrm{CBW})}{\overline{\mathrm{NE}_{\text{Gpregnancy}}}} \quad \text{feed for newborn calves culled to beef} \quad (8)$$

$$F_{\text{Gcalf}} = \left(\frac{2898}{6775}\right)\cdot\frac{(\mathrm{LWG}^{1/5})}{\overline{\mathrm{NE}_{\text{Gopen heifer}}}}\cdot\left[(\mathrm{LSW})^{271/200} - \mathrm{CBW}^{271/200}\right] \quad \text{for calves, LSW} \le 100\text{ kg} \quad (9)$$

$$F_{\text{Gothers}} = F_{\text{Gcalf}} + \sum_{i=0}^{N_{\text{rations}}} \frac{(3.24\mathrm{SWG}^{0.97})}{\overline{\mathrm{NE}_{Gi}}\cdot\mathrm{MSBW}^{0.75}} \times\left[\mathrm{SBW}_{i+1}^{1.75} - \mathrm{SBW}_i^{1.75}\right] \text{for culls to beef, LSW} > 100\text{ kg} \quad (10)$$

where F_{Gi} is the cumulative feed consumed (kg) that was deposited as body mass in the animal; CBW is calf birth weight (kg); $\mathrm{NE}_{\text{G-Pregnancy}}$ is the net energy of the ration for pregnant animals (MJ kg^{-1}); LWG is the live weight gain (kg day^{-1}) for calves till they reach a weight of 100 kg; LSW is the live sale weight (kg) for animals culled to beef; SWG is shrunk weight gain (kg day^{-1}), defined as 0.96*LWG; MSBW is mature shrunk body weight (kg), defined as 0.96*(mature body weight); SBW is shrunk body weight (kg), defined as 0.96*(live body weight). In equation (8), $\mathrm{NE}_{\text{Gpregnancy}}$ should be estimated based on the ration that pregnant animals consume in the final 80 days of pregnancy; this will be a combination of the bred heifer ration and the dry cow ration based on the herd cull rate.

Fig. 2 presents the feed energy cascade for dairy cattle; the arrow weights are indicative of the precedence of energy utilization, and explain why the dry cow ration is the most relevant for estimation of $\mathrm{NE}_{\text{Gpregnancy}}$. After manure and enteric methane energy, net feed energy is used for maintenance and lactation before growth or pregnancy. Because animals are typically dry the final 60 days of pregnancy, the dry animal ration is used for estimation of $F_{\text{Gnew born}}$.

The sum over rations in equation (10) is dependent on the beginning and ending animal weights (or equivalently ages – since $\mathrm{SBW}_2 = \mathrm{SBW}_1 + \mathrm{SWG}^*[\mathrm{Age}_2 - \mathrm{Age}_1]$ associated with each ration. Obviously the shrunk sale weight determines the final term in the sum.

2.1.5. Dataset of 536 farms and simplified regression approach

Since the calculation for individual animals is relatively data intensive, the opportunities of predicting AR by a simple regression function of the ratio of the kg milk and kg beef sold were tested and evaluated on the complete set of 536 farms for which such data are available.

2.1.6. Comparison between results of various allocation methods

The newly developed allocation approach is compared with revenue based allocation, protein content allocation and separation based allocation:

Revenue based allocation. The allocation was based on five-year average milk and beef sale prices (2004–2008 averages). The price data used as obtained from the USDA Agricultural Price Summary Tables (USDA NASS, 2004–2008), are presented in Table 1;

Protein content allocation. The AR calculated by the Food and Agriculture Organization (FAO) uses a protein content approach (Gerber et al., 2010). For calculation of the protein-content-based AR, we have used the culled (to beef) animal weight and standard lean cut protein content estimates and reported milk protein content from the individual farm surveys to estimate the protein produced on the farm in the form of meat and milk, respectively. We have assumed a carcass yield (live weight to hot carcass) of 58% and a yield cut (carcass weight to boneless close trimmed retail cut) of 57%, and finally 30% protein content for the lean meat (NDSU, 1999); and

Separation based allocation. In addition to the milking parlor related emissions, it may be suggested that GHG emissions associated with lactating animals should be completely attributed to milk production. We have made another estimate of the AR based on the fraction of all feed consumed on the dairy farm that is consumed by lactating animals; this is based on the direct relationship between feed consumed and quantity of manure and enteric methane released (Thoma et al., 2013a). Thus the unallocated whole farm emissions from feed consumed, enteric methane, and manure management are assigned directly to milk (a simple approach to system separation in the ISO standard sense) on the basis of the fraction of the entire herd's ration that is consumed by lactating animals. The remaining unallocated emissions were then split between milk and beef using the AR calculated as described in this paper.

2.2. Cream–milk allocation

Post farm gate, there is an important additional allocation required to account for excess cream reaching the fluid milk processing stage. As presented by Thoma et al. (2013a), at the sector level, this allocation subtracts more from the fluid milk GHG emissions estimate than the allocation to beef at the farm. For the milk processing stage, during standardization, where milk fat is initially separated then re-mixed to provide uniform milk fat content for each type of fluid milk product, a series of co-products are produced: whole, 2%, 1%, skim milk and excess milk fat (cream) (USDA AMS, 2007). The data collected for this study (Nutter, Ulrich, Kim, & Thoma, 2013) does not provide sufficient resolution at the processor level to allocate processor specific impacts among the products: in fact, most of the energy requirements are volume or mass based, e.g., pasteurization energy will be insensitive to milk fat content. We have used a mass-balance approach based on the assumption that the incoming milk burden to the processing facility is associated entirely with milk solids. Non-fat milk solids are assumed to follow the water stream through the process. This approach is based on the work of Feitz et al. (2007). We have used the national milk consumption rates for different milk fat content products coupled with a milk fat solids mass balance to derive allocation factors. Information from the USDA regarding the standard composition of different milk products was used to determine the composition of each type of milk on a fat-free basis (USDA NAL, 2010). There is little difference (other than fat content) between the different milk types, therefore we have assumed that only the fat is redistributed and that the protein and other non-fat solids are carried with the water as it is distributed among the milk products.

Raw milk is delivered to the processing plant, stored in refrigerated tanks, and then enters the pasteurization process. It is during this stage that the milk fat, as an approximately 40% fat content stream, is separated from the, now skim, milk stream. Depending on the desired fat content of the packaged milk (i.e., whole, 2%) a portion of the milk fat is mixed back into the fluid milk during homogenization. Thus, different amounts of the separated skim milk and cream are mixed to create the desired milk fat content. Each of the fluid milk products is assigned a GHG burden at the processor loading dock in proportion to the quantity of cream that is added to create the specific milk product. Excess cream is stored in a refrigerated tank and typically transported from the facility to produce ice cream, butter and other products. The proportion of the incoming milk burden that is attributed to the excess cream is removed from the fluid milk value chain at this point as shown in the Sankey chart presented by Thoma et al. (2013b).

USDA NASS (2009) published milk fat content reports for all dairy producing states; these reported values were used to create a regional weighted average of cream production. This information was combined with the product specification to complete a mass balance for determining the assignment of burdens of cream.

Table 1
Sales price data used for revenue based allocation.

Year	Cows[a] ($ cwt^{-1})	Steers and heifers ($ cwt^{-1})	Calves ($ cwt^{-1})	Milk ($ cwt^{-1})
2004	50.3	90.2	119	16.13
2005	51.7	94.3	135	15.19
2006	46.6	92.3	133	12.96
2007	47.9	95.4	119	19.22
2008	50.6	94.5	110	18.45

[a] Beef cows and cull dairy cows sold for slaughter (USDA NASS, 2004–2008); Currency is USA dollars.

3. Results and discussion

3.1. Farm-gate allocation

Detailed information from 536 farms (Popp et al., 2013) regarding the rations fed to the dairy herd, milk production and the number and weight of animals culled to the beef sector in the US were used to calculate the AR for the feed separation-based causal allocation described in Section 2.1. One situation that can occur and requires additional consideration is when animals are sold from one dairy to another. In this case, the environmental burdens should follow the animals sold and would be incurred by the dairy purchasing the replacement animals. In principle, this simply adds a third co-product to the system. The allocation to replacement heifers or mature animals sold to dairy can be calculated by simply adding a term to estimate the feed consumed by these animals and following the generalized version of equation (3); however, the regression analysis presented here would not be directly applicable.

Calculation of the feed required for the growth of animals on the farm requires the most detailed information. Table 2 presents the average, seasonally-weighted net energy content available for growth and lactation for rations for each of six animal classes on typical farms in the US. Table 2 is derived from sample rations presented in Table S1 through Table S5 in the supplementary information. These rations approximate the energy content of rations used to create Figs. 4 and 5. The energy contents used to create the high, low and average lines in the figures were obtained

Table 2
Individual feed-weighted net energy content for sample rations.

Animal class	Net energy parameter (MJ kg^{-1} DMI)[a]	Low energy density ration	High energy density ration	Average energy density ration
Open heifers	NE growth	2.91	3.70	4.69
Bred heifers	NE growth	2.91	3.59	4.49
Springers	NE growth	3.44	3.92	4.15
First-calf heifers	NE growth	4.66	4.61	4.80
Mature cows	NE growth	4.66	4.61	4.70
Dry cows	NE growth	3.30	3.92	4.23
First-calf heifers	NE lactation	6.95	6.79	6.96
Mature cows	NE lactation	6.95	6.79	6.82

[a] DMI, dry matter intake.

by taking the average of the seasonally-weighted net energy of the rations from all 536 farms and, assuming a normal distribution, determining the 95% lower and upper confidence limits (as 1.96*standard deviation); the farms chosen for the rations given in the Supplementary material fall almost exactly on top of these hypothetical energy density profiles. Figs. 4 and 5 provide a graphical means for estimating the quantity of a ration necessary to grow an animal of a given weight for Holsteins and Jerseys. It should be noted that the cumulative feed consumed in these figures does not represent all of the feed that the animal has consumed during the time that it gained the weight; rather it represents only that feed that was directly responsible for the animals' weight gain. It does not include maintenance nor feed consumed that may have been converted to methane in the rumen or lost as manure. These two figures represent the solution to the piecewise integral in equation (7). In general it is observed that a ration that contains more readily digestible, high-energy feeds is more efficient at providing animal body mass, but, based on the example rations in supporting Table S2, there is not a large difference in the net energy for lactation. Based on the data from the survey there is not a statistically significant difference between the predominantly Holstein farms ($n = 511$) and predominantly Jersey farms ($n = 25$; $p > 0.1$). The log-mean, production-weighted causal allocation factor for all farms is 0.915 ± 0.03 (95% CI). For revenue based allocation the production-weighted mean is 0.944 ± 0.02 (95% CI); for protein based allocation: 0.95 ± 0.002 (95% CI); and for the separation option: 0.97 ± 0.01 (95% CI).

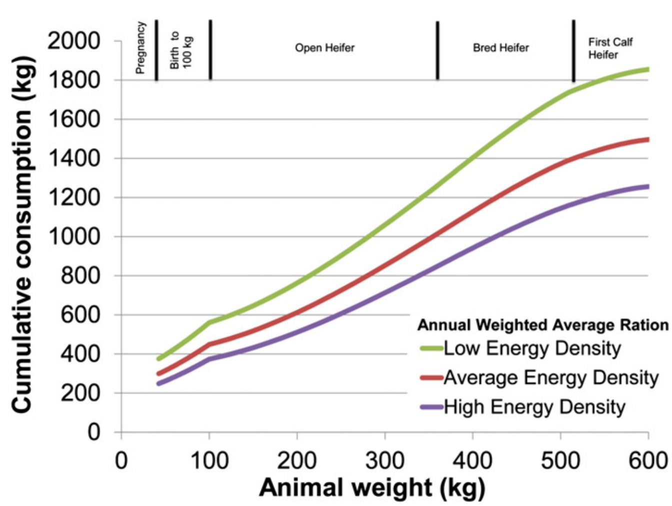

Fig. 4. Cumulative feed consumption required for different rations for Holstein dairy cow with a mature weight (following second calf) of 650 kg. Birth weight is approximately 46 kg.

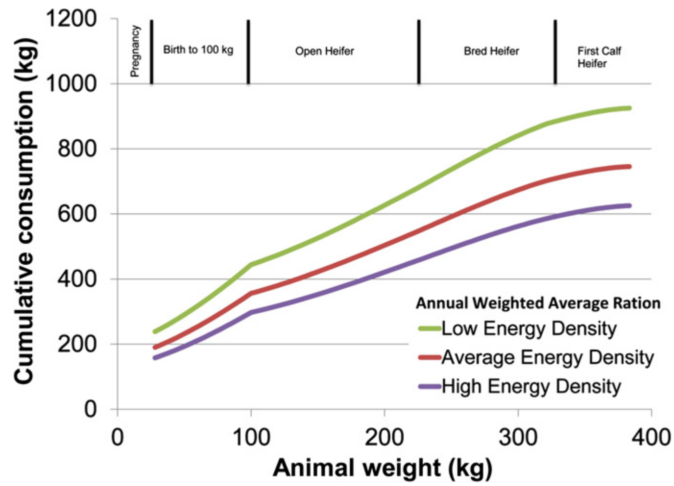

Fig. 5. Cumulative feed consumption required for different rations for Jersey dairy cow with a mature weight (following second calf) of 410 kg. Birth weight is approximately 28 kg.

Fig. 6 presents a comparison of the four methods for estimating the AR, by plotting the AR as a function of the kg beef sold per kg milk produced (BMR) on the farm. In principle, certain activities on the farm should be excluded when the AR is applied to the overall farm emissions; this would include energy and refrigerants, for example, used in the milk parlor. However, very few farms reported refrigerant usage, and none of the farms had metering data that would have allowed separation of electricity or other energy consumption between the milking parlor and other farm activities, and therefore in the analysis presented in Fig. 6 the AR has been applied to the entire farm emissions.

Milk yield and replacement rate are clearly important factors in dairy operations, and will influence the AR. Milk yield increases derived from increased feed consumption will, naturally, result in increased allocation to milk. However, yield increases resulting from more efficient feed conversion will lower the allocation to milk. The effect of replacement rate is inherently included in the analysis, most simply through the BMR parameter that is directly proportional to the replacement rate (given the pseudo-steady state assumption behind this model). Given this, it should be noted that this method should not be applied in situations where

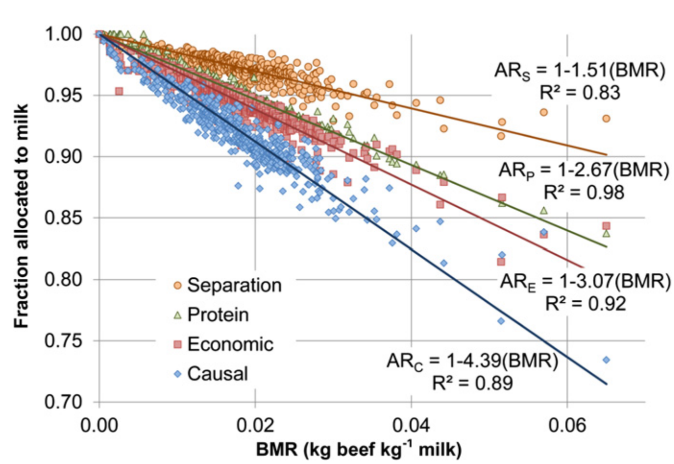

Fig. 6. Comparison of three approaches to allocation in dairy production. The BMR (kg beef sold per kg fat and protein corrected-milk produced) is calculated based on the live weight of all animals sold to the beef sector, including bull calves. The denominator of the BMR is the annual production of 4% fat, 3.3% protein corrected milk.

Table 3
Allocation to different fluid milk products with a basis of 100 kg FPCM delivered to processing plant.[a]

Parameter	Whole milk[b]	Reduced fat milk (2%)	Low fat milk (1%)	Fat-free milk (skim)	Cream	Total
Fat content (%)	3.27	1.98	0.97	0.08	40	
Non-fat solids content (%)	8.6	8.81	9.11	9.08	9.1	
Water content (%)	88.1	89.2	89.9	90.8	50.9	
Total sales (10^6 kg)	7938	8742	5257	3971	1524	27432
Raw milk distribution to different products	28.9	31.9	19.2	14.5	5.6	100
kg milk fat solids per 100 kg FPCM[c]	0.95	0.63	0.19	0.01	2.22	4.00
kg non fat solids per 100 kg FPCM	2.49	2.81	1.75	1.31	0.51	8.86
Fat distribution (%)	23.7	15.8	4.7	0.3	55.6	100
Milk product allocation burden (%)	26.9	27.2	15.4	10.7	19.8	100

[a] Production of various products is based on 2007 national consumption data.
[b] Milk fat and water composition of packaged milk: http://www.nal.usda.gov/fnic/foodcomp.
[c] FPCM, fat and protein corrected-milk.

there are appreciable changes in the herd structure over the course of a year, as the pseudo-steady state assumption will be violated.

3.2. Milk processor allocation

The allocation fractions in the last row of Table 3 are applied to operations in the plant that cannot be directly assigned (i.e., first of the ISO hierarchy approaches) to a specific process (e.g., energy and materials for blow molding containers is fully assigned to the packaging stage) including the raw milk burden and transportation to the plant. The allocation is computed by calculating the sum of all GHG emissions to the processor gate, assuming the entire dairy farm-gate burden for raw milk is assigned to milk solids. All the raw milk burdens, except those associated with milk fat solids that are allocated by mass (the first row in Table 3) and the milk fat burden are distributed according to the milk fat content (in the second row). The final result is given in the overall allocation row, yielding a fraction allocated to the different milk types of 80.2%; 19.8% being allocated to cream.

4. Conclusions

For a given farm where we know fat- and protein-corrected milk production and cull rates by animal class, we can calculate the AR based on milk production and cumulative weight of animals leaving the farm to the beef industry. The AR would then be used to assign all GHG emissions (except those clearly associated with milk production, e.g., refrigeration and milking parlor energy usage, but including enteric and manure management emissions) between milk and beef. Allocation is an important step in attributional LCA because it can appreciably alter the reported results. It is therefore very important to have a completely transparent approach to performing the allocation in order for studies conducted by different research groups to be comparable. The full causal analysis is data intensive and mathematically cumbersome; however, a parsimonious solution arises when looking at the simple correlation between the mass of meat to milk produced on an individual farm and can be given by the equation of Fig. 6 ($AR_c = 1\text{–}4.39 \cdot BMR$). Since physical causality is preferred in the ISO hierarchy over economic allocation or single parameter-based allocation (protein), the causal approach is of high interest and has been adopted by the International Dairy Federation to ensure consistency between studies (IDF, 2010).

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.idairyj.2012.08.012.

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