

Meat, dairy, and more

Analysis of material, energy, and greenhouse gas flows of the meat and dairy supply chains in the EU28 for 2016

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Abstract

To decarbonize the European Union, protein consumption must transition to diets low in meat and dairy which will drastically change the material and energy flows in current meat and dairy supply chains. To understand the impacts on current flows, a baseline is required. Although recent studies have improved the scope of reported greenhouse gas (GHG) emissions, no quantitative overview exists including intermediate and final product flows. To address this knowledge gap, we structured the meat and dairy supply chains into a connected set of transformation nodes and distribution nodes. The former are processes transforming inputs into outputs, whereas the latter distribute the outputs to other processes using them as inputs. Currently, livestock play a central role in agriculture and other industries through the consumption of 271 Mt fodder crops, 108 Mt grain, 85 Mt grazed biomass, 49 Mt oil meal, and 16 Mt feed by-products. This feed is transformed into 64 Mt dairy and 35 Mt meat which ensures that the EU28 is a net exporter of meat and dairy while providing 25 Mt of by-products. This production also leads to 435 Mt CO₂-eq. with the main contribution from beef cattle (35%), dairy cattle (32%), and swine (20%). Thus, the lower GHG intensities of dairy products compared to meat do not imply a low contribution to the total emissions. By mapping the material, energy, and GHG emission flows, we have created a baseline suitable for identifying potential supply chain changes and their related GHG increase or decrease resulting from the protein transition.

KEYWORDS

climate change, industrial ecology, livestock, meat and dairy, socioeconomic metabolism, supply and use tables

1 | INTRODUCTION

The supply chains in the meat and dairy sector are responsible for 15% of total greenhouse gas (GHG) emissions in the European Union member states (EU28) (European Environment Agency, 2012; FAO, 2017a). Decarbonizing the EU28 is required to reach the objective of keeping the increase in average global surface temperature under 2°C compared to the pre-industrial period, especially if striving for the 1.5°C as ratified in the Paris Agreement in 2016 (UNFCCC, 2015). To achieve this, the European Commission (2011) has agreed to reduce domestic GHG emissions within the EU by 80–95% in 2050 compared to 1990. To reach these targets also the GHG emissions in the meat and dairy supply chains in the EU need to be reduced substantially.

One possible decarbonization pathway is the substitution of meat and dairy products by alternative protein sources. To assess the GHG emission reduction potential of such a shift, the current meat and dairy supply chains must be compared to the supply chains of alternative products. In the

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meat and dairy sector, the supply chains consist of multiple processes. First, agricultural inputs are manufactured such as fertilizer and pesticides. These are used to cultivate fodder crops, grains, grazed biomass, and oil-bearing crops. Part of these feed sources, together with by-products from other industries, can be further processed into compound feed and other products. The resulting feed is consumed in livestock husbandry which produces livestock and raw milk. Subsequently, the livestock is slaughtered and either only cut into pieces (primary meat) or further processed (secondary meat), for example into sausages or smoked meat. Furthermore, the raw milk undergoes dairy processing into a wide variety of products. Finally, the meat and dairy go through distribution and retail to the consumer. Additionally, processes such as transport, packaging, and the production of capital goods can be considered. The climate change impacts of the main products of these supply chains, such as beef and milk, and alternatives have been compared through life cycle assessment (LCA) studies (Broekema & van Paassen, 2017; Clune, Crossin, & Verghese, 2017; Mattick, Landis, Allenby, & Genovese, 2015; Smetana, Mathys, Knoch, & Heinz, 2015; Tuomisto & Teixeira De Mattos, 2011). However, many processes also produce by-products such as hides and whey. To isolate the impact of a particular meat or dairy product, GHG emissions are allocated between the main product and by-products whenever a process produces multiple products. As a result, comparing LCA results of meat and dairy with alternatives do not include the replacement of by-products. Alternatively, substitution and system expansion could in principle incorporate the impact of by-products, but results would likely vary considerably depending on how this is implemented. Thus, the calculated emission reduction potential is less certain. To more accurately assess the impact of dietary shift scenarios, a comprehensive baseline is required of the GHG emissions and economic flows of the meat and dairy supply chains.

Current studies have focused on total GHG emissions of the meat and dairy supply chains or GHG emissions per unit of meat and dairy product (Supporting Information S1). Lesschen, van den Berg, Westhoek, Witzke, and Oenema (2011) calculated European GHG emissions and total production of beef, cow's milk, pork, poultry, and eggs using the MITERRA model but limited the analysis of the supply chains to fertilizer manufacturing, feed cultivation, and livestock husbandry. A study by Weiss and Leip (2012) expanded the scope by including meat and milk from sheep and goats as products. Additionally, GHG emissions were included from transport and LULUC. More recently, FAO quantified the GHG emissions for different world regions, with the EU member states divided between Western and Eastern Europe, through the Global Livestock Environmental Assessment Model (GLEAM) (FAO, 2017b; Gerber et al., 2013). GLEAM further expanded the scope by including buffalo products and emissions from the primary processing of meat and dairy, the production of capital goods such as farming equipment, and packaging. Although these studies have improved the scope of reported GHG emissions, no quantitative overview exists that includes the intermediate product and final product flows, and in particular the by-product flows.

We aim to address this knowledge gap by quantifying GHG emissions and economic flows of meat and dairy supply chains. This study includes the production and processing of dairy cattle, beef cattle, swine, chicken, turkey, sheep, and goat. The method is based on open source statistical sources and scientific literature, thus ensuring that the results can be replicated and updated with new annual data.

2 | METHODS

To quantify the economic flows of the meat and dairy supply chains within the EU28 and the related GHG emissions from production, we applied an adapted version of the general system structure (GSS) for modeling socioeconomic metabolism developed by Pauliuk, Majeau-Bettez, and Müller (2015). Public data were used to ensure the replicability of the study.

2.1 | General system structure for socioeconomic metabolism

The GSS was developed by Pauliuk et al. (2015) to harmonize different methods which are applied in sustainability assessment studies such as life-cycle assessment and material flow analysis (Pauliuk et al., 2015). They show that the underlying structure of these methods is the bipartite directed graph. Graphs are mathematical structures in graph theory consisting of points and connecting lines called vertices and edges, respectively (Weisstein, 2019c). If the edges indicate a connection in one direction, it is called "directed" (Weisstein, 2019b). For bipartite graphs, the vertices can be divided into two distinct groups where the vertices in one group are not connected by edges to each other, but only to vertices in the other group (Weisstein, 2019a). Thus, a bipartite directed graph only has edges indicating connections in one direction between these two groups of vertices. Additionally, bipartite directed graphs can be represented as supply and use tables which is an existing underlying structure of input-output tables.

Pauliuk et al. (2015) argue that several sustainability assessment methods can be generalized through bipartite directed graphs with two distinct groups of nodes: transformation nodes (TN) and distribution nodes (DN). For example, the systems in LCA commonly consist of processes connected by economic inputs and outputs. These processes may have inputs extracted from and outputs emitted to the environment. This is similar to considering unit processes as TNs and flows as edges. To turn this into a bipartite directed graph, the direct flows between processes must be disconnected and first go into another node which transfers flows between unit processes. The advantage of structuring nodes into TNs and DNs is that it is not necessary to specify which TN the input of another TN originates from. This structure is incorporated in Ecoinvent 3 with the addition

TABLE 1 Supply and use tables

| | Supply | | | | | Use | | | | |
|---|----------|----------|----------|--------|---|----------|----------|----------|--------|--|
| | I | O | M | DN | | I | O | M | DN | |
| P | V_{ip} | V_{op} | V_{mp} | DO_p | P | U_{ip} | U_{op} | U_{mp} | DI_p | |
| B | V_{ib} | | | | R | U_{ir} | | | | |

P, set of all economic flows (p, index for set); I, set of all transformation nodes (i, index for set); R, set of all resource flows (r, index for set); B, set of all emission flows (b, index for set); O, set of all other economic activities within the EU28 (o, index for set); M, set of all economic activities outside the EU28 (m, index for set); V_{xy} , supply of y (placeholder for p,b,r) by x (placeholder for i, o, m); U_{xy} , use of y (placeholder for p, b, r) by x (placeholder for i, o, m); DI_p , input of p in distribution nodes; DO_p , Output of p from distribution node.

of “a market activity” as DNs which aggregate similar outputs from different processes together before being used as inputs in other processes (Ecoinvent, 2019).

2.2 | Adaptation of GSS for structuring data

In this study, the GSS was adapted for the analysis of meat and dairy supply chains. The original framework consists of the production industries and waste treatment industries as TNs and the corresponding product markets and waste markets as DNs. The products eventually go to the final use phase where they provide services to agents and are turned into waste. The industries, markets, and final use phase all have stocks of materials and energy. The agents and final use provide the labor and capital requirements of the industries. The SEM also interacts with the biophysical environment through the resources and emissions.

For our analysis, we excluded stock changes, labor, capital, and capital goods such as vehicles and buildings due to a lack of data. Additionally, products and waste were both treated as economic flows unlike the original GSS where they were explicitly treated as separate categories. Correspondingly, TNs represent both production processes and waste treatment. Since we did not include consumption in our system boundaries, there is no explicit final consumption phase; instead, economic flows were provided to the economy beyond the analyzed supply chains. Additionally, we make the following distinction within the system environment based on geographical location: the system environment within the same geographical region as the system, and the system environment outside of that geographical region. This differentiates imports and exports from the supply of goods to consumers and businesses within the EU.

Table 1 presents the Supply and Use Tables (SUTs) of the adapted GSS. The SUTs are linked by Equation (1) which states that for any particular economic flow the use of a product is equal to its supply.

$$\sum_i U_{ip} + \sum_o U_{op} + \sum_m U_{mp} = DI_p = DO_p = \sum_i V_{ip} + \sum_o V_{op} + \sum_m V_{mp} \quad (1)$$

2.3 | System boundary

In this study, the meat and dairy supply chains in the EU28 of dairy cattle, beef cattle, swine, chicken, turkey, goat, and sheep are assessed. The supply chains consist of 11 production TNs, a TN representing extra-EU trade, and a TN representing the rest of the EU economy. Figure 1 presents the flowchart of TNs and the flows between them as mediated by the DNs. The cultivation of fodder crops, grains, and grazed biomass were grouped into feed cultivation. The cultivation and processing of soybeans, rapeseed, and sunflower seeds were included as oil meal is a major feed input for livestock. Further, distribution and retail only include the energy use for storage of goods. Moreover, the manufacturing of agricultural inputs was excluded to retain the focus on mapping the by- or co-products; the production of fertilizers and pesticides is complex and would require significant effort to combine available data. Additionally, transport was not included due to the highly aggregated level of available data, though in principle transport could be added as a separate TN that transforms energy and material inputs into transport service outputs. The full list of economic and environmental flows in each TN can be found in Supporting Information S2.

2.4 | Greenhouse gas emission sources

The following GHG emission sources emitted within the EU28: N volatilization, enteric fermentation, manure management, and fuel combustion. GHG emissions related to LULUC and GHG emissions other than CO_2 , CH_4 , and N_2O were excluded. To add and compare the impact of included emissions, the GWP₁₀₀ emission factors of IPCC 5 were used (Myhre et al., 2013); the GWP₁₀₀ values for CH_4 and N_2O are 28 and 265 CO_2 -eq., respectively. The GHG emissions resulting from electricity were calculated using carbon intensity factors of each EU28 member state (Moro & Lonza, 2017) as found in Supporting Information S4. For heat, GHG emissions were calculated based on the assumption that natural gas or oil are used as fuel resulting in a carbon intensity factor of 56 to 74 kg CO_2 per GJ_{LHV} (Blok & Nieuwlaar, 2017).

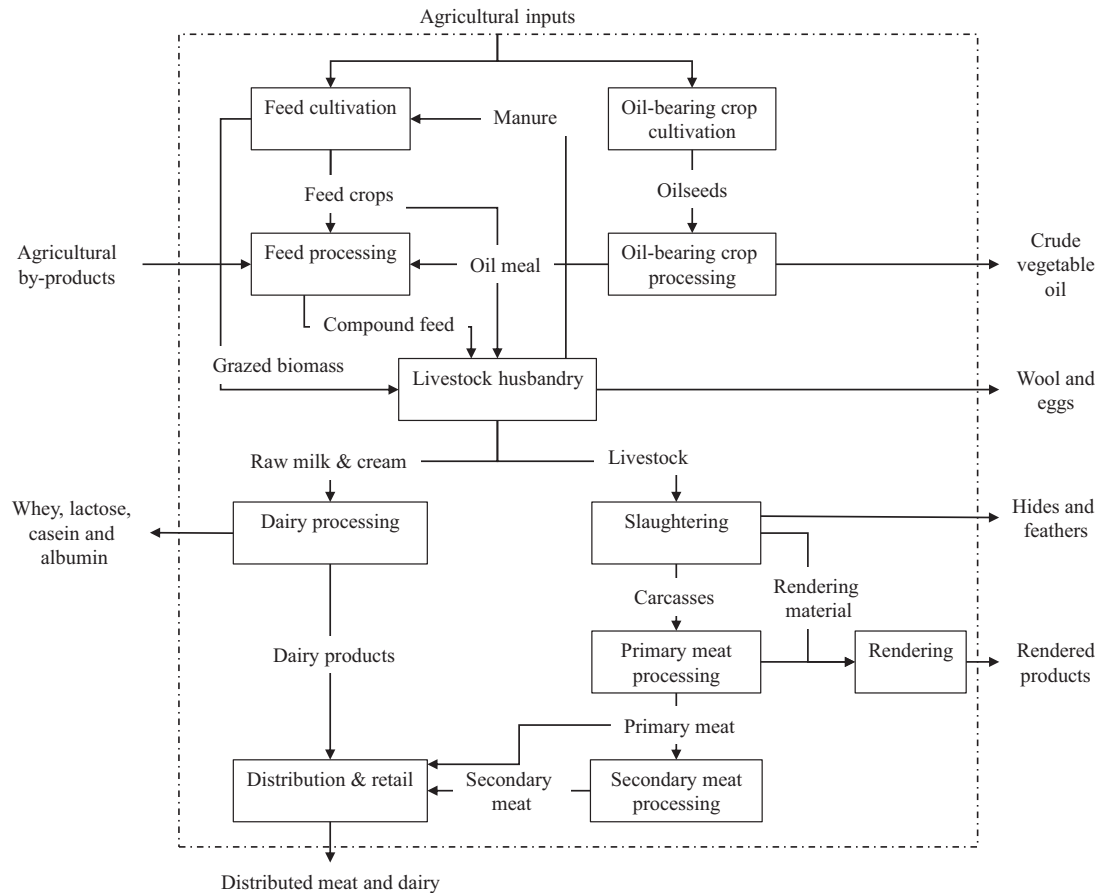


FIGURE 1 Economic flows to and from transformation nodes in the EU28 meat and dairy supply chain excluding the production of agricultural inputs and environmental, energy, and extra-EU28 trade flows

2.5 | Data sources and data handling

Ensuring replicability, public data sources were used in this study. The principle data sources were Eurostat, FAOSTAT, and the EU vegetable oil and protein meal industry association (FEDIOL) (Supporting Information S2). For each dataset, the annual data was standardized into the following categories: the flow type, that is, whether it is supply, use, a resource, or an emission; TN; TN country location; flow name; unit. To aggregate data with different names and levels of detail, the flow names were categorized to match the 123 economic and 27 environmental flows (Supporting Information S2). The data was collected per member state to more precisely reveal data gaps and to calculate electricity related GHG emissions with national carbon intensities. For data gaps, the value of the nearest available year to 2016 was used. However, when no data was available for an economic flow, supplementary literature was used to estimate the missing values (Supporting Information S2). Finally, the resulting data was aggregated for the EU28.

Next, data was extracted from the SUTs for analysis. First the pre- and post-livestock husbandry supply chains were analyzed with Sankey diagrams. The former starts at the cultivation of fodder crops, grains, grazed biomass, and oil-bearing crop cultivation and ends at livestock husbandry while the latter starts at livestock husbandry and ends at distribution and retail. For the post-livestock Sankey diagram, we have only included dairy and beef supply chains to illustrate the complexity of the economic flows. In addition, an overview is given of the economic flows for each livestock category. Finally, the quantified GHG emissions are presented for the EU28 meat and dairy supply chain. The complete SUTs on which the results were based can be found in Supporting Information S3.

3 | RESULTS

We will analyze the results in the SUTs (Supporting Information S3) in three sections. First, we explore the cultivation and processing of feed through a Sankey diagram. Second, we give an overview of the final products for each livestock categories. Finally, we analyze the total GHG emissions and GHG emission intensity of the different livestock categories.

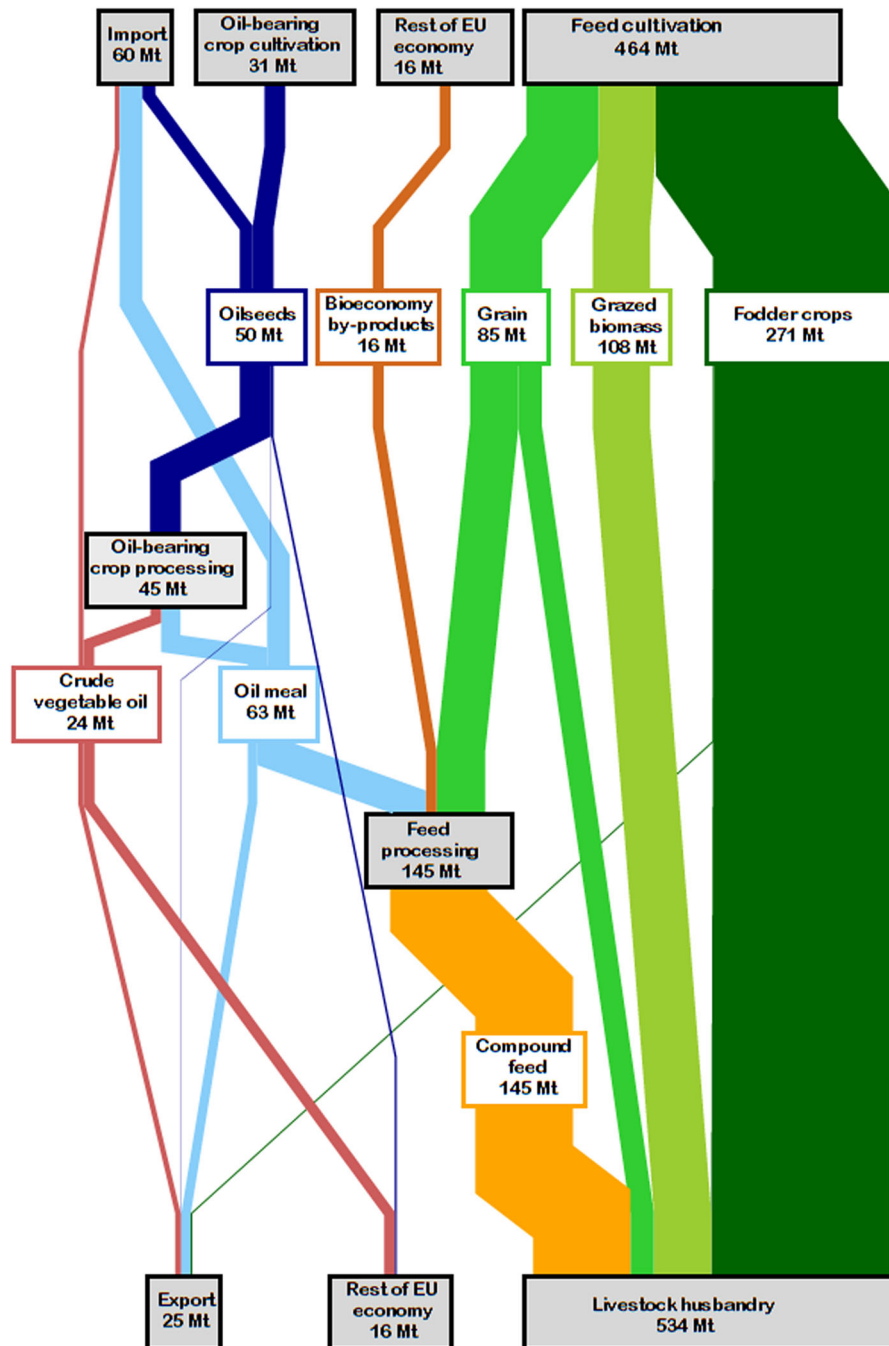


FIGURE 2 Sankey diagram of the products (white boxes) and processes (gray boxes) of the feed supply chain in Mt of wet mass until the input of feed materials into livestock husbandry excluding water, fertilizer, manure, and pesticide inputs for feed and oil-bearing crop cultivation for 2016. Underlying data used to create this figure can be found in Supporting Information S8 (Comext, 2018; Eurostat, 2018a; FEDIOL, 2010; Prodcom, 2018) [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

3.1 | Feed cultivation, oil-bearing crop cultivation and processing, and feed processing

The Sankey diagram (Figure 2) shows the biomass flows of the feed supply chain aggregated for all livestock categories in 2016. Energy and other flows such as fertilizer and manure are excluded but can be found in the complete SUTs (Supporting Information S3).

The bulk of biomass for feed is cultivated in the EU28. The total production is 271 Mt fodder crops, 108 Mt grains, and 85 Mt grazed biomass. The quantity of grain for feed was estimated at 36% of the total grain production based on the general fraction of crops used for feed (Cassidy, West, Gerber, & Foley, 2013). This is supplemented with an additional 49 Mt of oil meal and 16 Mt of by-products from agriculture, food, and industrial processing. The import and export of fodder crops, grains, grazed biomass, and by-products is below 1%, so the production is mostly for

consumption as feed in the EU28. In contrast, oil meal and oilseeds are traded more extensively. In the EU28, 49 Mt of oilseeds are processed into 29 Mt oil meal and 16 Mt crude vegetable oil. Of the 49 Mt oilseeds, 36% comes from net import; furthermore, there is an additional net import of 20 Mt oil meal. In contrast, crude vegetable oils have a net export equivalent to 3% of EU28 production. In the case of soy, the net import of soybeans is 60% and the net export of crude soy oil is 22%. The high import of soy results from the low soy production in the EU28, while soy constitutes 61% of the overall 49 Mt oil meal consumption in the EU28. This may indicate that oil meal, in particular soy meal, drives the demand and import of oilseeds while crude vegetable oils are the by-product.

These different feed sources are either fed directly to livestock or further processed into compound feed. Compound feed is composed of 50% grain, 39% oil meal, and 11% agricultural by-products. The total production is 145 Mt which together with 271 Mt fodder crops, 85 Mt grazed biomass, and the remaining 35 Mt grain result in 534 Mt of feed consumed by livestock in 2016.

3.2 | Livestock husbandry, product processing, and distribution and retail

We analyzed the production of final products for seven livestock categories from livestock husbandry, slaughtering, meat processing, dairy processing, rendering, and distribution and retail (Supporting Information S3). In Table 2, we give an overview of the total EU28 supply and extra-EU import of final products from each livestock category. The table is organized to split the primary products and by-products from each other, so the total mass of each can be shown. Furthermore, the Sankey diagram (Figure 3) illustrates the product flows of beef and dairy cattle supply chains to exemplify how the processes are connected. All outputs are on an annual basis for 2016 and the percentages are based on weight.

Annually, the EU abattoirs slaughter 7,368 million chicken and turkey, 259 million swine, 50 million sheep and goat, and 26 million cattle (Eurostat, 2018d). The resulting carcasses are processed into 35 Mt primary meat of which 42% is further processed into secondary meat. The largest source of meat is swine (51%) followed by chicken (26%) and cattle (17%). Meat from cattle comes from both beef and dairy cattle, the latter providing around 45%. The overall meat from import is relatively low at 2% of the total availability with only a significant import of sheep meat at 16%. The export is more extensive with an overall export of 12% of available meat. The largest share of the exported meat comes from swine (64%), chicken (25%), and beef cattle (9%). Overall, the output of meat in the EU28 is 27% of the total output on mass basis.

Besides meat, livestock husbandry and slaughtering produce other common livestock products. Chicken annually produce 7 Mt eggs and 0.1 Mt feathers. In practice, laying hen and broiler chicken are separate production systems. However, the available data does not distinguish their contribution to meat, so in our model they are aggregated. Cattle, sheep, and goat also produce 1.5 Mt of hides while sheep additionally produce wool. In total, eggs are 5% of the total output on mass basis in the EU28 with hides, wool, and feathers only constituting 1%.

The slaughtering and processing of carcasses also results in waste material. The fraction of waste material ranges from 25% to 57% of the total live weight for the different livestock. This material is further treated as rendering material in the rendering process which removes water and potential pathogens. The resulting outputs are 12 Mt of rendered fats and protein. These rendering products are used as input for fertilizers, pet-feed, and various other industrial and cosmetic products (Marti, Johnson, & Mathews, 2012). Rendering products together are about 9% of the total output on mass basis in the EU28.

In addition, dairy cattle, sheep, goat produce 168 Mt raw dairy, 97% coming from dairy cattle. This is processed within the EU28 into 35 Mt drinking milk, 10 Mt cheese, 8 Mt acidified milk, and 8.1 Mt of other dairy products. The import of dairy is less than 1% of the total available dairy products. However, the export is more significant for the available dairy powder (37%), concentrated milk (27%), buttermilk (21%), and processed cheese (17%). These products are suitable for long distance transport as dairy powder, concentrated milk, and cheese have long shelf-life due to their reduced water content. In total, the dairy export is only 6% of the available dairy products. However, if in raw dairy equivalent the export is 11% assuming the following raw milk per product ratios based on Eurostat (2017): 1.1 kg raw milk per kg skimmed milk, 9.7 kg per kg dairy powder, 4.9 kg per kg concentrated milk, 7.7 kg per kg cheese, 1 kg per kg drinking milk, and 1.1 kg per kg buttermilk. In total, the output of dairy is 48% of total output in the EU28 on mass basis.

Dairy processing also results in 11.8 Mt of by-products. The largest fraction is whey, the by-product of cheese production, which constitutes 95% of these by-products. Lactose and lactalbumin are derived from whey and form 4% of the dairy by-products. The final by-product is casein which is generally isolated from skim milk (Tetra Pak, 2018). Though small in quantity, these products are important inputs for the food and pharmaceutical sectors (Gutiérrez, Hamoudi, & Belkacemi, 2012). Altogether, the dairy by-products are 9% of the total output on mass basis of the meat and dairy supply chains in the EU28.

Overall, 131.5 Mt products are produced by the meat and dairy supply chains in the EU28. Of this total, 75.3% are meat and dairy combined and 5.4% are eggs on a mass basis. The final 19.3% are by-products linking the meat and dairy supply chains to other industries ranging from other food sectors to the pharmaceutical sector. Meat and dairy imports are generally insignificant, so the EU28 consumption is supplied by EU28 production. For both meat and dairy, the EU28 is a net exporter at 12% of the available meat and for dairy 6% on mass basis or 11% of raw milk equivalent. This shows that the EU28 is self-sufficient for its consumption, while also exporting a substantial portion of meat and dairy to extra-EU markets.

TABLE 2 Product supply and import in Mt from livestock husbandry, processing, rendering, and distribution in the EU28 in 2016

| Products | Dairy cattle | | Beef cattle | | Swine | | Chicken | | Turkey | | Sheep | | Goat | | Total | |
|-------------------------------|--------------|------------|-------------|------------|-------------|------------|-------------|------------|------------|------------|------------|------------|------------|------------|--------------|------------|
| | Supply | Import | Supply | Import | Supply | Import | Supply | Import | Supply | Import | Supply | Import | Supply | Import | Supply | Import |
| Primary meat ^a | 2.7 | | 2.4 | 0.2 | 6.6 | | 7.0 | 0.1 | 1.2 | | 0.7 | 0.1 | | | 20.6 | 0.5 |
| Secondary meat | | | 0.9 | | 11.3 | | 2.0 | 0.3 | 0.4 | | | | | | 14.7 | 0.3 |
| Drinking milk | 34.7 | 0.3 | | | | | | | | | 0.6 | | 0.3 | | 35.7 | 0.3 |
| Cream | 2.8 | | | | | | | | | | | | | | 2.8 | |
| Dairy powder | 2.6 | | | | | | | | | | | | | | 2.6 | |
| Concentrated milk | 1.1 | | | | | | | | | | | | | | 1.1 | |
| Acidified milk | 8.0 | | | | | | | | | | | | | | 8.0 | |
| Butter | 2.2 | | | | | | | | | | | | | | 2.2 | |
| Cheese | 9.9 | 0.1 | | | | | | | | | 0.2 | | 0.2 | | 10.3 | 0.1 |
| Processed cheese | 0.6 | | | | | | | | | | | | | | 0.6 | |
| Buttermilk | 0.5 | | | | | | | | | | | | | | 0.5 | |
| Egg | | | | | | | | | | | | | | | 7.2 | |
| Total primary products | 65.0 | 0.5 | 3.3 | 0.2 | 17.9 | 0.2 | 16.2 | 0.4 | 1.6 | 0.4 | 1.5 | 0.1 | 0.6 | 0.1 | 106.1 | 1.2 |
| Rendered products | 1.5 | | 1.5 | | 5.6 | | 2.5 | | 0.4 | | 0.4 | | | | 12.0 | |
| Hide | 0.6 | | 0.7 | 0.1 | | | | | | | 0.1 | | | | 1.5 | 0.1 |
| Feathers | | | | | | | | | | | | | | | 0.1 | |
| Wool | | | | | | | | | | | | 0.1 | | | 0.0 | 0.1 |
| Whey, concentrated | 2.1 | 0.1 | | | | | | | | | | | | | 2.1 | 0.1 |
| Whey, liquid | 7.3 | | | | | | | | | | | | | | 7.3 | |
| Whey, powder | 1.8 | | | | | | | | | | | | | | 1.8 | |
| Lactose | 0.3 | | | | | | | | | | | | | | 0.3 | |
| Lactalbumin | 0.2 | | | | | | | | | | | | | | 0.2 | |
| Casein | 0.1 | | | | | | | | | | | | | | 0.1 | |
| Total by-products | 13.9 | 0.1 | 2.3 | 0.1 | 5.6 | 0.3 | 2.5 | 0.4 | 0.4 | 0.4 | 0.5 | 0.1 | 0.6 | 0.1 | 25.4 | 0.3 |
| Total products | 78.9 | 0.5 | 5.6 | 0.3 | 23.5 | 0.0 | 18.8 | 0.4 | 2.1 | 2.0 | 2.0 | 0.2 | 0.6 | 0.1 | 131.5 | 1.5 |

Note. Underlying data used to create this table can be found in Supporting Information S3.

^aExcluding primary meat used in secondary meat processing.

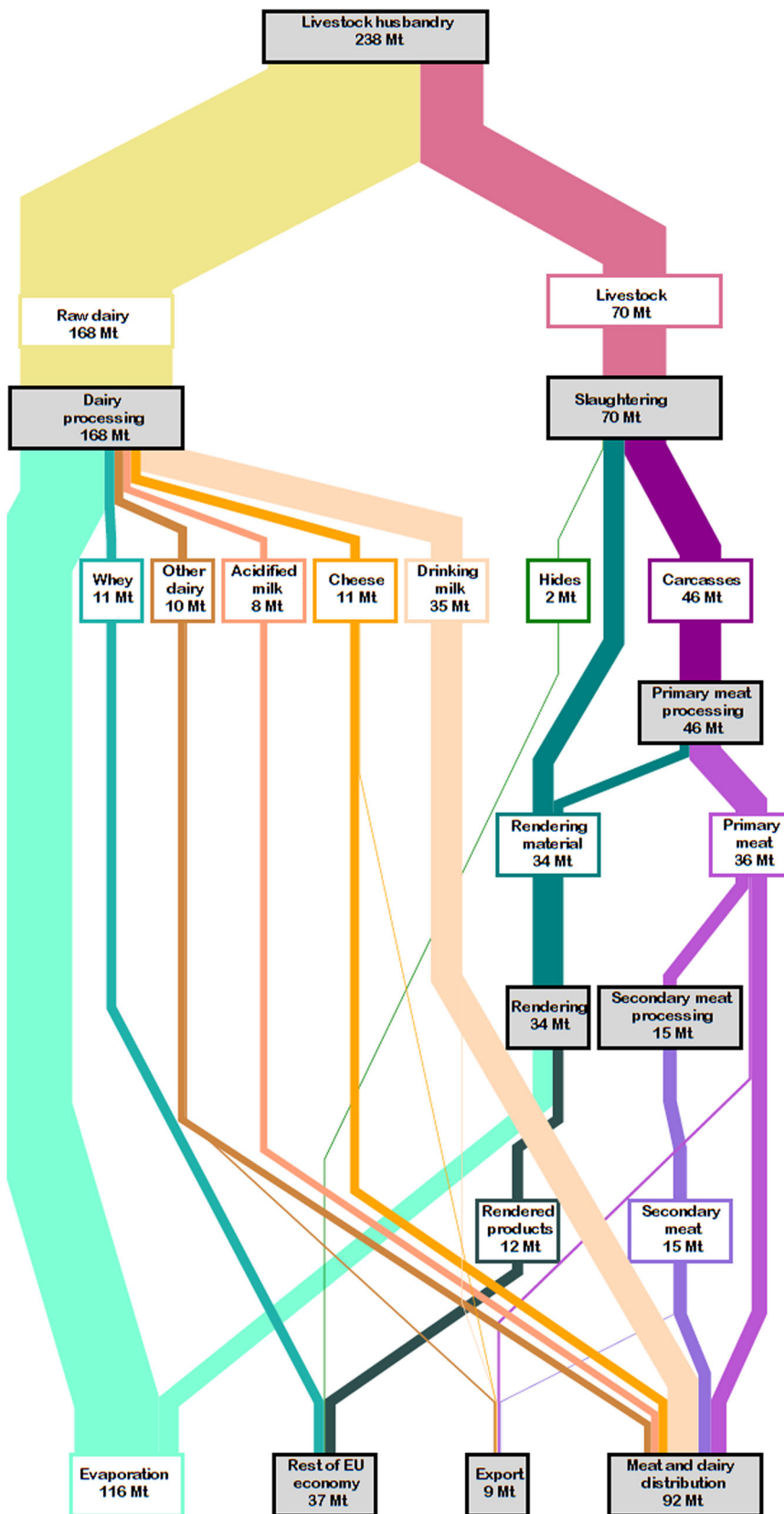


FIGURE 3 Sankey diagram of the products (white boxes) and processes (gray boxes) of the livestock product supply chain in Mt of wet mass from livestock husbandry until the output into meat and dairy distribution, the rest of the EU28 economy, and extra-EU export for 2016. Underlying data used to create this figure can be found in Supporting Information S8 (Comext, 2018; Eurostat, 2018b, 2018c, 2018d; Prodcom, 2018) [Color figure can be viewed at wileyonlinelibrary.com]

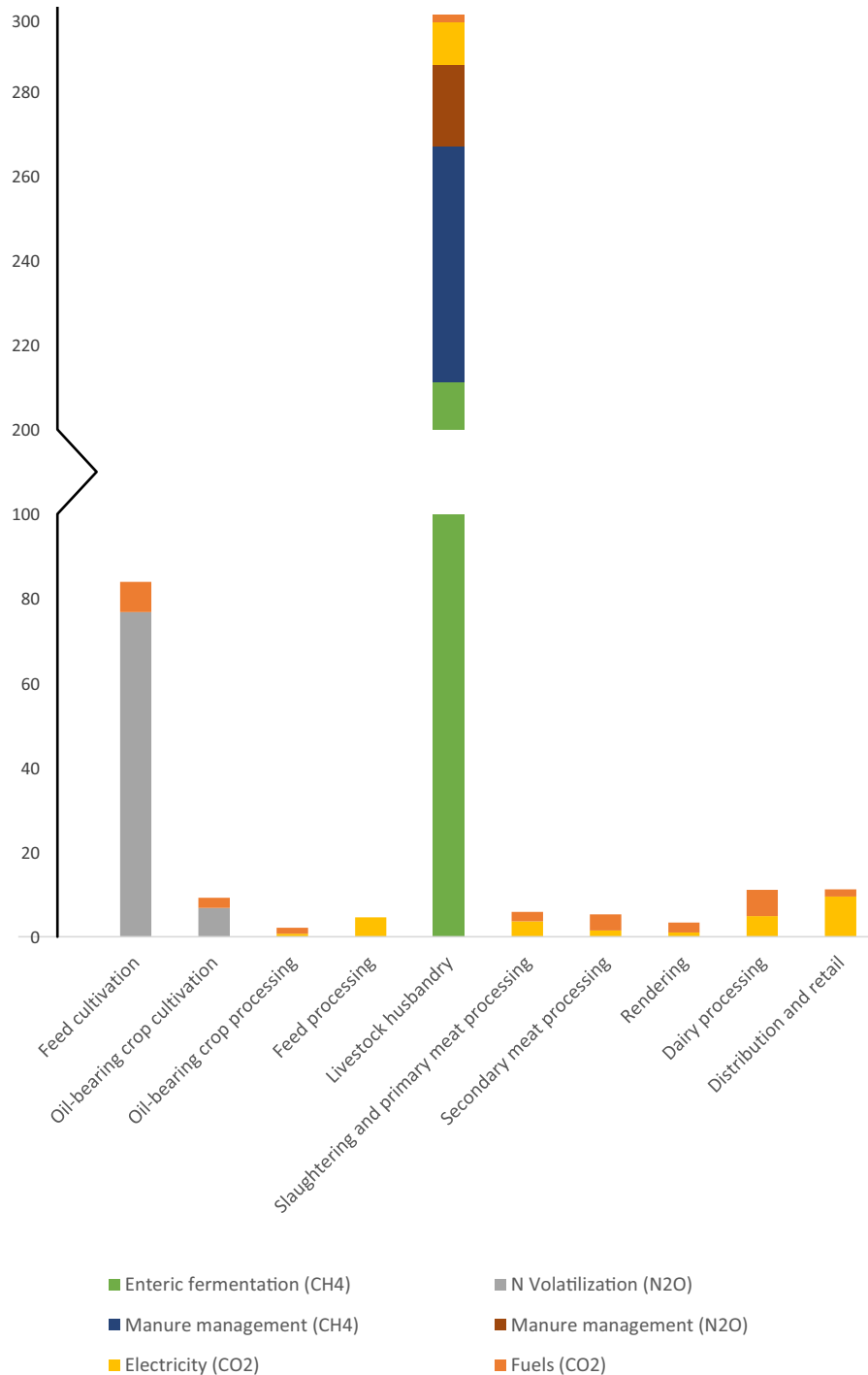


FIGURE 4 GHG emissions per source and per transformation node in the EU28 meat and dairy supply chain in 2016. Underlying data used to create this figure can be found in Supporting Information S9 [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

3.3 | Greenhouse gas emissions

The GHG emissions from production in the EU28 meat and dairy supply chains in 2016 were estimated to be around 434.9 (427.0–442.8) Mt CO₂-eq. These emissions originate from enteric fermentation (211 Mt CO₂-eq., in the form of CH₄), N volatilization (84 Mt CO₂-eq., in the form of N₂O), manure management (75 Mt CO₂-eq., in the form of CH₄ and N₂O), electricity generation (36 Mt CO₂), and fuel use (29 Mt CO₂) (Figure 4). The largest contributors to the total GHG emissions are beef cattle (35%), dairy cattle (32%), and swine (20%) (Figure 5); surprisingly, sheep (7%) emit more GHG emissions than chicken (5%) despite chicken producing more than 10 times the amount of primary products (Table 2).

A different picture emerges when the total GHG emissions are divided by the amount of meat and dairy products. When assigning all impact to meat and dairy by mass, beef cattle and sheep have the highest GHG emissions per kg at 46.2 and 19.2, respectively. Dairy cattle and goats have

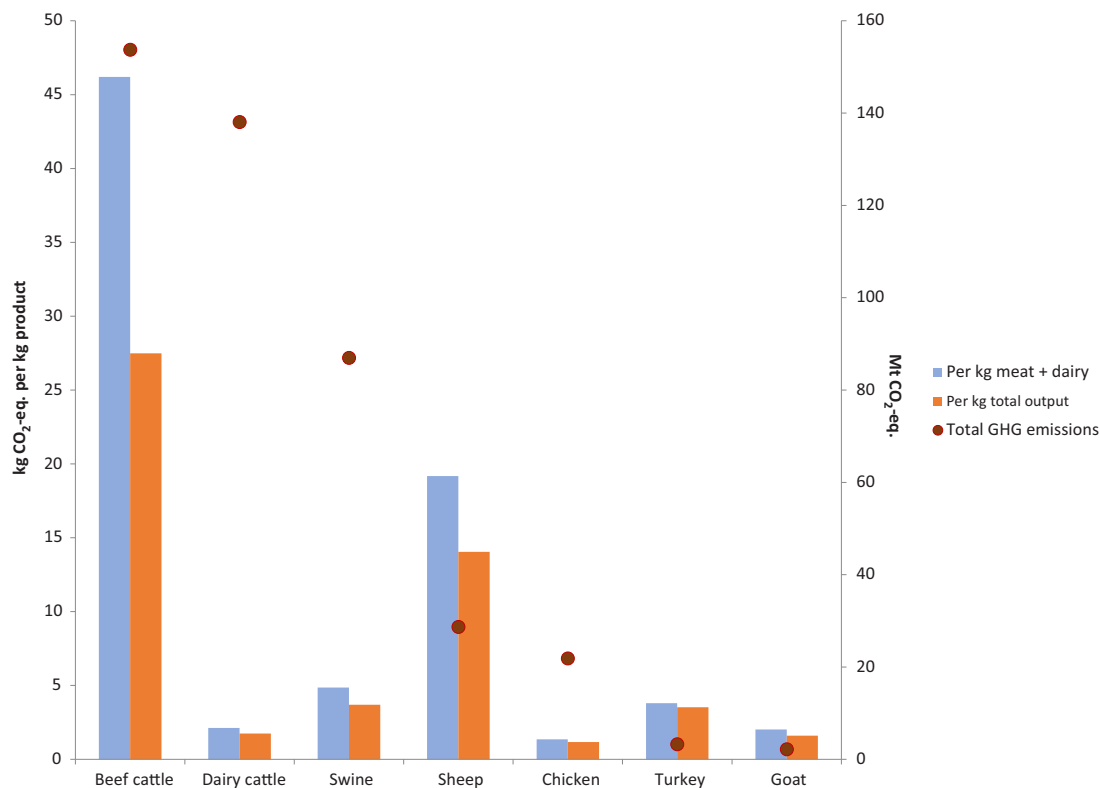


FIGURE 5 GHG emissions per livestock category given as the total GHG emissions, per kilogram of the total mass of products, and per kilogram of primary products in 2016. Underlying data used to create this figure can be found in Supporting Information S10. See Supporting Information S6 for the division of feed related emissions to each livestock category [Color figure can be viewed at wileyonlinelibrary.com]

much lower values despite being ruminants due to the productivity of dairy production. Table 2 shows that beef cattle produce only 3.3 Mt of meat compared to dairy cattle with a comparable amount of meat (2.7 Mt) but an additional 62.4 Mt of dairy products. Though sheep also produce dairy, the balance is much more equal with 0.7 Mt meat and 0.8 Mt dairy. Dividing the total GHG emissions by the total output instead of only meat and dairy leads to a reduction of emission intensity of beef cattle and sheep relative to other livestock. This is due to the relatively large quantities of by-products from ruminant meat processing compared to dairy processing and non-ruminant meat processing. However, the general outcome does not change. Overall, ruminants focusing on dairy can have similar GHG per kilogram product values as non-ruminants; however, the sheer number of dairy cattle still results it in being the second largest GHG emitter after beef cattle.

4 | DISCUSSION

4.1 | Comparing greenhouse gas emissions with previous studies

Despite having a similar conclusion that livestock husbandry and cultivation are the largest emission sources, the total GHG emissions of 0.4 Gt CO₂-eq. in this study differs from outcomes in previous studies. Although the results are similar to those of Lesschen et al. (2011), total emissions from Weiss and Leip (2012) and FAO (2017c) are markedly higher at 0.6–0.8 and 0.7 Gt CO₂-eq., respectively. These differences could be due to different system boundaries and GWP₁₀₀ values. As FAO's GLEAM model is most similar to the model in our study with respect to the included processes and livestock categories, we compared our GHG emissions with each GHG source in the GLEAM data (FAO, 2017c) (Table 3).

To make the results comparable, we adjusted our results by harmonizing GWP₁₀₀ and by extending the system boundaries to include processes and GHG emissions included in GLEAM but excluded in the model of our study. For assessing climate change impact, our study used the GWP₁₀₀ from IPCC AR5 which, compared to GLEAM, lowers the values from 298 to 265 CO₂-eq. for N₂O and 34 to 28 CO₂-eq. for CH₄. Adjusting to the older values, our results increase by 69.2 Mt CO₂-eq. To harmonize the system boundaries, the GHG emissions related to land use change, transport, and manufacturing of fertilizers were added. First, the LUC emissions of GLEAM were added which increased our results by 67.5 Mt CO₂-eq. Second, to include transport of livestock to slaughterhouses, raw milk to dairy processors, and meat to retail, the distance and carbon intensity values of GLEAM were used to estimate transportation (Table S5-1 in Supporting Information S5); this increased our results by 3.3 Mt

TABLE 3 Comparison between the results of FAO's GLEAM and this study in Mt CO₂-eq., the additional emissions of harmonizing GWP₁₀₀ values (Myhre et al., 2013), and the estimated emissions from excluded processes (Aguilera et al., 2015; FAO, 2017b, 2017c)

| | GLEAM | This study | Harmonize GWP ₁₀₀ | Estimate excluded processes | Adjusted values |
|--------------------------------------|-------|--------------------|------------------------------|--|-----------------|
| Feed (CO ₂) | 116.5 | 9.5 | | +16.6–22.0 (average 19.3) ^a | 28.8 |
| Feed: Fertilizer and crop residues | 59.3 | 30.1 | +1.9 | | 32.0 |
| Feed: Applied and deposited manure | 78.3 | 53.6 | +7.7 | | 61.3 |
| LUC: Soy and palm | 67.5 | | | +67.5 ^b | 67.5 |
| Enteric fermentation | 224.2 | 211.3 | +45.3 | | 256.6 |
| Manure management (CH ₄) | 66.1 | 55.6 | +11.9 | | 67.5 |
| Manure management (N ₂ O) | 32.4 | 19.3 | +2.4 | | 21.7 |
| Direct energy | 20.9 | 16.5 | | | 16.5 |
| Indirect energy | 8.1 | | | +8.1 | 8.1 |
| Post-farm (including transport) | 33.6 | 39.0 | | +3.3 ^c | 42.3 |
| Total | 706.9 | 434.9 ^d | +69.2 | +99.0 | 602.3 |

^aTable S5-1 in Supporting Information S5.

^bFAO (2017c).

^cTable S5-2 in Supporting Information S5.

^dDifference from sum of results due to rounding.

CO₂-eq. Third, we estimated GHG emissions of fertilizer manufacturing by using the values in Table S5-2 in Supporting Information S5. This results in an increase of 16.6–22.0 Mt CO₂-eq. These adjustments increase the GHG emissions of our study to 602.3 Mt CO₂-eq.

The difference between GLEAM and our study remains at around 100 Mt CO₂-eq. The difference between “Feed: Fertilizer and crop residues” can be explained due to the use of tier 1 data from FAOSTAT in our study and the use of a tier 3 methodology in GLEAM. The difference between the estimated feed (CO₂) emissions could not be clarified as the GLEAM documentation (FAO, 2012a) includes neither disaggregate emission data nor sufficient emission factor values to reconstruct this GHG emission category.

4.2 | Implications for modeling transitions to meat and dairy substitutes

The impact of substituting meat and dairy is often calculated based on the difference in carbon footprint with the substitutes. For example, the EAT-Lancet Commission establishes the carbon footprints of major food groups based on global averages and adjusts these values in different scenarios based on projected efficiency gains (Willett et al., 2019). One underlying assumption is that the structure of other linked industries does not fundamentally change; the only change is either an increase or decrease in production. Our results indicate that this may simplify the GHG reduction estimates too much because the meat and dairy supply chains play an important role as consumers of feed by-products and producers of goods beyond meat and dairy.

If meat and dairy products are substituted, other uses must be found for the feed by-products. Although the by-products only constitute 3% of the total feed consumption, they are significant outputs for various industries. For example, the EU bioethanol industry produces 4 Mt of animal feed or 42% of their total output on mass basis (ePure, 2017). Likewise, the EU produces 3.4 Mt of brewer's spent grain, about 20 kg per 100 L of beer, which is mostly used for feed production (Lynch, Steffen, & Arendt, 2016). Furthermore, if crude vegetable oil consumption remains 16 Mt, another use for 29 Mt of oil meal must be found. Using these by-products to substitute goods or inputs in other industries could lead to a further GHG reduction.

Additionally, the main by-products of meat and dairy supply chains will need to be replaced. Our results show that rendered product at 12 Mt and whey at 11 Mt are the by-products with the greatest quantity. For rendered products, Luske and Blonk (2009) have analyzed the GHG impact of substitutes. By using their carbon footprint values for 12 Mt of product, we estimate that the total GHG emissions of the substitutes would be 18–37 Mt CO₂-eq. For whey, alternative protein sources are required. Conventional soy protein is an existing option which may have a lower GHG impact than whey (Braun, Muñoz, Schmidt, & Thrane, 2016). In addition, insect-based protein and other novel protein sources are being researched (Smetana, Palanisamy, Mathys, & Heinz, 2016). More research is required to assess the climate change impact of these alternative proteins. Overall, the replacement of by-products requires the production of additional products that likely will decrease the GHG reduction substituting meat and dairy.

In conclusion, transitioning to a widescale adoption of low meat and dairy diets would result in major changes for the broader bio-economy. These changes are not captured by comparing the carbon footprints of various food items or diets. However, a scenario with the absolute material flows as a baseline could be used to explore the impact of such transitions.

4.3 | Limitations

Our analysis has the following three main limitations: aggregation of product flow, method of allocation, and exclusion of other environmental emissions. We will address these issues and suggest improvements for further research.

The first limitation is the use of aggregated products. For example, offals and edible fats were included in primary meat. Also, rendered fats and rendered proteins were aggregated into rendered products since the individual quantities were not known. Another aspect to look into is the amount of grain fed to livestock. It is now assumed that 36% of grain production in the EU28 is used as feed which is based on Cassidy et al. (2013). For a more accurate figure, it may be possible to quantify other uses for grain to isolate the fraction used in feed. Furthermore, because feed is aggregated for the different livestock, GHG emissions from cultivation till retail cannot be compared. One possible method to disaggregate feed is to use existing data on feed inputs per unit of livestock. This calculation should then be verified with the aggregated feed values. Overall, the aggregations were required due to a lack of more detailed information, but this can be improved in further research.

Second, these estimates do not follow standard LCA allocation procedures. Generally, if there are co-products from a process, or unit-process in LCA terminology, the emissions and inputs need to be allocated to the different outputs. Instead, we in the first case grouped only meat and dairy products together and allocated all emissions to them; as the mass flows were known, this was done on a mass basis. If economic allocation was applied, the GHG emissions per kilogram meat and dairy would likely be larger. In the second case we allocated the emissions to the total output, but there would be no difference with an economic allocation as everything was assigned to the aggregate product.

Although this does not give an overview of the emissions for each product, it was sufficient to emphasize the difference in view between total GHG emissions and GHG emissions per unit product. For example, dairy cattle in particular has a high total GHG emissions, but low GHG emissions per unit product compared to livestock with mainly meat products. This relative difference in emission intensity is also shown in LCA's with milk (1.29 kg CO₂-eq.) and yoghurt (1.31 kg CO₂-eq.) per kilogram produce having less impact than beef (26.61 kg CO₂-eq.), pork (5.77 kg CO₂-eq.), and chicken (3.65 kg CO₂-eq.) per kilogram bone-free meat (Clune et al., 2017). Other dairy products have higher GHG intensities, for example, cheese and butter at 8.55 and 9.25 kg CO₂-eq. per kilogram produce, respectively. However, the total output of dairy livestock will still have lower GHG emissions per product, because drinking milk (35.7 Mt) and yoghurt (8.0 Mt) are a much larger share of the total dairy output compared to cheese (10.3 Mt) and butter (2.2 Mt). So, despite the methodological differences, the overall conclusions remain in line with existing LCA's.

Finally, our analysis does not include social, economic, and other environmental indicators which are of interest to the Sustainable Development Goals. This is a limitation to use our results as a baseline, since meat and dairy are linked to issues such as water use (FAO, 2018), biodiversity loss (FAO, 2019; WWF, 2017), poverty and nutrition (FAO, 2012b). However, the method and baseline developed in this study could provide the starting point to further add indicators for a more comprehensive overview and baseline of the meat and dairy supply chains.

5 | CONCLUSION

In order to create a baseline for low meat and dairy scenarios in the EU28, we quantified the product flows and GHG emissions of the meat and dairy supply chain for 2016. Statistical data were structured into 123 economic flows, 27 GHG emission sources, and 13 processes through supply and use tables. This enabled analyzing the role of the meat and dairy supply chains in the EU28.

First, the meat and dairy supply chains consume 271 Mt fodder crops, 108 Mt grain, 85 Mt grazed biomass, 49 Mt oil meal, and 16 Mt feed by-products. Import and export is only important for oilseeds and oil meal with a net import of 36% and 41% of the aggregate of production of import, respectively. This trade appears to be driven by the demand for feed. Further, livestock plays an important role as a consumer of by-products from other industries despite these by-products only constituting 3% of total feed consumption. To conclude, the meat and supply chains play a central role in agriculture and other industries as a major consumer of fodder crops, grains, grazed biomass, oil meal, and by-products.

Second, the meat and dairy supply chains produce 64 Mt dairy, 35 Mt meat, 7 Mt eggs, and 25 Mt by-products. The largest sources of meat are swine, chicken, and cattle. Dairy cattle produce 45% of cattle meat, but they also produce 97% of the 168 Mt raw dairy. The EU28 imports little additional meat and dairy, whereas it exports 12% of available meat and 6% of available dairy. Besides the EU28 consumption of most meat and dairy, the net export also seems to drive production in the EU28. Resulting from this production, the meat and dairy supply chains provide 12 Mt rendering products, 11 Mt whey, and 2 Mt other by-products for use in other industries. Overall, the meat and dairy supply chains ensure that the EU28 is self-sufficient in meat and dairy while providing food and non-food by-products.

Third, the meat and dairy supply chains emit an estimated 434.9 (427.0–442.8) Mt CO₂-eq. Beef cattle emit 35% of these emissions largely due to CH₄ from enteric fermentation and swine emit 20% due to manure management emissions. Surprisingly, dairy cattle are the second largest emitters (32%) despite having similar GHG per kilogram product values as non-ruminants. This result shows that low GHG per kilogram product values do not guarantee low total GHG emissions; thus, this implies that carbon footprints should be supplemented with the total GHG emission values.

Finally, our baseline is designed to assess the impact of adopting low meat and dairy diets. The by-products that were consumed by livestock could substitute other goods leading to further GHG reductions. In contrast, replacing meat and dairy by-products would lead to more GHG emissions. By quantifying the product flows, our study provides a suitable baseline to show where choices must be made for modeling large-scale transitions to meat and dairy substitutes, but further research is required to include additional indicators.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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REFERENCES

- Aguilera, E., Guzmán, G. I., Infante-Amate, J., Soto, D., García-Ruiz, R., Herrera, A., Villa, I., Torremocha, E., Carranza, G., & González de Molina, M. (2015). Embodied energy in agricultural inputs. Incorporating a historical perspective. *Documentos de Trabajo de la Sociedad Española de Historia Agraria 1507*, Sociedad Española de Historia Agraria. <https://ideas.repec.org/p/seh/wpaper/1507.html>
- Blok, K., & Nieuwlaar, E. (2017). Analysis of energy chains. In *Introduction to energy analysis* (2nd ed., pp. 145–164). Abingdon, Oxfordshire: Routledge.
- Braun, M., Muñoz, I., Schmidt, J. H., & Thrane, M. (2016). Sustainability of soy protein from life cycle assessment. *FASEB Journal*, 30, 894–895.
- Broekema, R., & van Paassen, M. (2017). *Milieu-effecten van vlees en vleesvervangers*. Retrieved from <http://www.blonkconsultants.nl/2017/12/07/ambiental-impact-of-meat-substitutes/?lang=en>
- Cassidy, E. S., West, P. C., Gerber, J. S., & Foley, J. A. (2013). Redefining agricultural yields: From tonnes to people nourished per hectare. *Environmental Research Letters*, 8(3), 034015. <https://doi.org/10.1088/1748-9326/8/3/034015>
- Clune, S., Crossin, E., & Verghese, K. (2017). Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, 140, 766–783. <https://doi.org/10.1016/j.jclepro.2016.04.082>
- Comext. (2018). *EU trade since 1988 by CN8 (DS-016890)*. Luxembourg: Eurostat.
- Ecoinvent. (2019). *What is a market and how is it created?* Retrieved from <https://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-is-a-market-and-how-is-it-created.html>
- ePure. (2017). *Main output of European renewable ethanol plants*. Retrieved from <https://www.epure.org/media/1631/main-output-of-european-renewable-ethanol-plants-2016.png>
- European Commission. (2011). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: *A Roadmap for moving to a competitive low carbon economy in 2050* (Report No. 52011DC0112). Brussels, Belgium: European Commission.
- European Environment Agency. (2012). *Annual European Union greenhouse gas inventory 1990–2010 and inventory report 2012* (Report No. 3/2012). Copenhagen, Denmark: European Environment Agency.
- Eurostat. (2017). *Utilisation of milk and dairy products obtained, EU-28, 2016 (million tonnes)*. Retrieved from [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Utilisation_of_milk_and_dairy_products_obtained_EU-28_2016_\(million_tonnes\).png](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Utilisation_of_milk_and_dairy_products_obtained_EU-28_2016_(million_tonnes).png)
- Eurostat. (2018a). *Crop production in EU standard humidity (apro_cpsh1)*. Luxembourg: Eurostat.
- Eurostat. (2018b). *Milk collection (all milks) and dairy products obtained—Annual data (apro_mk_pobta)*. Luxembourg: Eurostat.
- Eurostat. (2018c). *Production and utilization of milk on the farm—Annual data (apro_mk_farm)*. Luxembourg: Eurostat.
- Eurostat. (2018d). *Slaughtering in slaughterhouses—Annual data (apro_mt_pann)*. Luxembourg: Eurostat.
- FAO. (2012a). *Global livestock environmental assessment model. Version 2.0. Data reference year: 2010*. Rome, Italy: FAO.
- FAO. (2012b). *Livestock sector development for poverty reduction: An economic and policy perspective—Livestock's many virtues*. In J. Otte, A. Costales, J. Dijkman, U. Pica-Ciamarra, T. Robinson, V. Ahuja, C. Ly, & Roland-Holst D., (Eds.), Rome, Italy: FAO.
- FAO. (2017a). *Global livestock environmental assessment model. Version 2.0. Supplement S1*. Rome, Italy: FAO.
- FAO. (2017b). *Global Livestock Environmental Assessment Model. Version 2.0. Data reference year: 2010*. Rome, Italy: FAO.
- FAO. (2017c). *Global Livestock Environmental Assessment Model (GLEAM) [Online]*. Retrieved from www.fao.org/gleam/en/
- FAO. (2018). *Water use of livestock production systems and supply chains—Guidelines for assessment (Draft for public review)*. Rome, Italy: FAO.
- FAO. (2019). *The state of the world's biodiversity for food and agriculture*. In Bélanger J., & Pilling D., (Eds.), Rome, Italy: FAO Commission on Genetic Resources for Food and Agriculture Assessments.
- FEDIOL. (2010). *Annual statistics*. Retrieved from http://sfx.scholarsportal.info/guelph/docview/1506173227?accountid=11233%0Ahttp://sfx.scholarportal.info/guelph?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kEv:mTx:bOok&genre=report&sid=ProQ:CANadian+Research+Index&atitle=&title=Annual+statistics&issn=&
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... Tempio, G. (2013). *Tackling climate change through livestock. A global assessment of emissions and mitigation opportunities*. Rome, Italy: FAO. <http://www.fao.org/3/i3437e/i3437e00.htm>

- Gutiérrez, L. F., Hamoudi, S., & Belkacemi, K. (2012). Lactobionic acid: A high value-added lactose derivative for food and pharmaceutical applications. *International Dairy Journal*, 26(2), 103–111. <https://doi.org/10.1016/j.idairyj.2012.05.003>
- Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. P., & Oenema, O. (2011). Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*, 166–167, 16–28. <https://doi.org/10.1016/j.anifeeds.2011.04.058>
- Luske, B., & Blonk, H. (2009). *Milieueffecten van dierlijke bijproducten*. Gouda, the Netherlands: Blonk Milieu Advies.
- Lynch, K. M., Steffen, E. J., & Arendt, E. K. (2016). Brewers' spent grain: A review with an emphasis on food and health. *Journal of the Institute of Brewing*, 122(4), 553–568. <https://doi.org/10.1111/jib.363>
- Marti, D. L., Johnson, R. J., & Mathews, K. H. (2012). Where's the (not) meat? Byproducts from beef and pork production. *Journal of Current Issues in Globalization*, 5(4), 397–423. Retrieved from <http://search.proquest.com/openview/c2ff62665ad6c356a491d4c833a7eb50/1?pq-origsite=gscholar&cbl=2034844>
- Mattick, C. S., Landis, A. E., Allenby, B. R., & Genovese, N. J. (2015). Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. *Environmental Science & Technology*, 49(19), 11941–11949. <https://doi.org/10.1021/acs.est.5b01614>
- Moro, A., & Lonza, L. (2017). Electricity carbon intensity in European member states: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment*, 64, 5–14. <https://doi.org/10.1016/j.trd.2017.07.012>
- Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestedt, J., Huang, J., ... Zhang, H. (2013). *Anthropogenic and natural radiative forcing. Climate change 2013—The physical science basis* (pp. 659–740). Cambridge, UK: Cambridge University Press. <https://doi.org/10.1017/CBO9781107415324.018>
- Pauliuk, S., Majeau-Bettez, G., & Müller, D. B. (2015). A general system structure and accounting framework for socioeconomic metabolism. *Journal of Industrial Ecology*, 19(5), 728–741. <https://doi.org/10.1111/jiec.12306>
- Procom. (2018). *Sold production, exports and imports (DS-056120)*. Luxembourg: Eurostat.
- Smetana, S., Mathys, A., Knoch, A., & Heinz, V. (2015). Meat alternatives: Life cycle assessment of most known meat substitutes. *International Journal of Life Cycle Assessment*, 20(9), 1254–1267. <https://doi.org/10.1007/s11367-015-0931-6>
- Smetana, S., Palanisamy, M., Mathys, A., & Heinz, V. (2016). Sustainability of insect use for feed and food: Life cycle assessment perspective. *Journal of Cleaner Production*, 137, 741–751. <https://doi.org/10.1016/j.jclepro.2016.07.148>
- Tetra Pak. (2018). Casein. *Dairy processing handbook*. Retrieved from <https://dairyprocessinghandbook.com/chapter/casein>
- Tuomisto, H. L., & Teixeira De Mattos, M. J. (2011). Environmental impacts of cultured meat production. *Environmental Science and Technology*, 45(14), 6117–6123. <https://doi.org/10.1021/es200130u>
- UNFCCC. (2015, December). *Paris agreement*. Paper presented at the UNFCCC Conference of the Parties on Its Twenty-First Session, Paris. Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf
- Weiss, F., & Leip, A. (2012). Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems and Environment*, 149, 124–134. <https://doi.org/10.1016/j.agee.2011.12.015>
- Weisstein, E. W. (2019a). *Bipartite graph*. Retrieved from <http://mathworld.wolfram.com/BipartiteGraph.html>
- Weisstein, E. W. (2019b). *Directed graph*. Retrieved from <http://mathworld.wolfram.com/DirectedGraph.html>
- Weisstein, E. W. (2019c). *Graph*. Retrieved from <http://mathworld.wolfram.com/Graph.html>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., ... Declerck, F. (2019). Food in the anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393, 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- WWF. (2017). *Appetite for destruction*. Gland, Switzerland: WWF.

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