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Research article

Implications of a consumption-based accounting of greenhouse gas emissions from global dairy cattle systems

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ABSTRACT

Greenhouse gas (GHG) emissions from dairy systems at the national level are typically estimated at the point of production, following guidelines for national reporting. However, exploring the emissions allocated to the point of consumption also provides key insights into reducing emissions across all stages (inputs, production, trade, and consumption). In this study, the GHG emissions associated with global dairy cattle products were estimated using a consumption-based accounting approach. The analysis was based on data from 2015, covering 254 territories and considering 21 dairy cattle commodities. Our findings reveal that international trade in dairy products is dominated by a few countries, with the top 20 net importing/exporting countries accounting for about 70% of global emissions embodied in trade. Although, at the global level, GHG emissions embodied in the international trade of dairy cattle products represented a relatively small share of the total (133 Mt CO_2 eq, 9%), they were significant at the country level, particularly for countries heavily involved in trade. In some cases, imports accounted for more than 50% of consumption-related emissions. Trade among European Union countries was relevant representing 32% of the global GHG emission linked with the international trade of dairy products. By adopting a system-wide approach, this study aims to provide novel and critical information to reduce GHG emissions from the global dairy sector, contributing to initiatives such as Pathways to Dairy Net Zero. The results are discussed in the context of the importance of dairy products for global food security. The consumption-based analysis presented represents a different and original perspective in the computation of GHG emissions at the national level for a specific and relevant food item. This approach, guiding policymakers in identifying key impact areas across all stages of the supply chain, can foster the transition to low-carbon dairy products, and support circular economy practices.

1. Introduction

Accurate assessment of greenhouse gas (GHG) emissions is critical to better understand the global carbon cycle, support the development of climate policies, and project future climate change (Friedlingstein et al., 2022). GHG emissions are typically reported at the point of production of commodities or services; referred to as 'production-based' or sometimes as 'territorial' or 'geographical' emissions. This accounting method is typically used when countries report their emissions and set domestic targets in Nationally Determined Contributions, following the guidance laid out by the Intergovernmental Panel for Climate Change (IPCC) (IPCC, 2006), which states that mitigation only applies to GHG emissions occurring within national territories over which the country has jurisdiction. Accordingly, each country is held responsible for the GHG emissions originating within its national boundaries.

Although this approach allows focusing on domestic targets to reduce emissions, a country which only consumes imported goods could enjoy a high standard of living whilst being held accountable for only a low level of GHG emissions. Furthermore, each country – having jurisdiction only within its own borders – can influence the reduction of emissions only through national or local climate policies making the assumption sensible (Bastianoni et al., 2014; Karakaya et al., 2019), leading countries to only focus on the mitigation of domestic production, overlooking imported goods.

Against this background, investigating 'consumption-based' emissions – i.e. assigning emissions to the point of consumption of commodities by adjusting estimates to account for trade — provides a different perspective. Although consumption-based accounting is typically considered separately from traditional production-based accounting, it is not necessarily intended to replace the current method of calculating national emissions. Rather, it serves as a complementary approach, recognizing that mitigation efforts can be implemented on both the production and consumption sides (Tukker et al., 2020). It is also

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informative to understand the effect of allocating the emissions associated with exported products from exporting to importing countries (Caro et al., 2017). While different accounting approaches may be used to promote or support different policy arguments (Tukker et al., 2020), several studies have recommended that countries monitor emission transfers via international trade, in addition to territorial emissions, to mitigate global GHG emissions (Osei-Owusu et al., 2020; Fezzigna et al., 2019; Karakaya et al., 2019; Peters et al., 2012, 2011).

Agricultural production is a major driver of global warming (Campbell et al., 2017; Crippa et al., 2021). Global demand for agricultural products is expected to increase by 70%–100%, along with the predicted rise in the global population to 10 billion people by 2050 and changes in the per capita consumption (Tilman et al., 2011; UN, 2022). The livestock sector substantially contributes to GHG emissions worldwide (Caro et al., 2014a; Climate Watch, 2024; FAO, 2020). With livestock products being increasingly traded internationally and consumed away from where production takes place, the role of trade in national emissions accounting cannot be ignored (Caro et al., 2014b; Dalin and Rodríguez-Iturbe, 2016; Foong et al., 2022). Foong et al. (2022) explored differences between trade-adjusted agricultural emissions and production-based emissions for 1987 and 2015. The overall pattern was broadly similar across countries, but reinforced, between the two dates, i.e. both importers and exporters intensified their engagement in trade while China passed from being a net exporter to a net importer during this period. Shutters and Muneepeerakul (2012) remarked how agricultural trade is important for countries with insufficient domestic resource supplies, especially for populous and rapidly growing economies. In this context, trade stability is essential for regional and global food security, economic prosperity, and sustainable development. Hence, different allocations as well as different system boundaries and functional units of trade-related emissions, can determine different results of emissions at country level. Emissions are typically allocated at the point of production of commodities or services but assigning emissions to the point of consumption of commodities, by adjusting them to account for trade provides a different perspective that can complement production-based accounting method (Tukker et al., 2020).

According to FAOSTAT (2025), international trade of dairy cattle products significantly increased in the last two decades. From 2000 to 2021, trade in cow milk, cheese and butter increased by 106%, 130%, and 39%, respectively. World milk production is projected to grow at 1.8% p.a. (up to 1060 Mt by 2031) over the next decade, faster than most other agricultural commodities. Globally, around 30% of milk is expected to be processed into butter, cheese, skimmed milk powder, whole milk powder or whey powder in the coming decade — but with very large geographical variation (OECD and FAO, 2022). High-income countries tend mostly to consume processed dairy products while low- and middle-income countries tend mostly to consume fresh dairy products. Milk production in the latter is expected to grow by about 40% to 2030, and about 80% of this growth will comprise fresh dairy products (OECD-FAO, 2021).

The aim of this work is to estimate the GHG emissions linked to global dairy products with a consumption-based accounting approach for 2015. Overall, 21 dairy cattle commodities are considered in this study. The analysis is performed at the global level (254 territories) using specific country estimates. A special emphasis is given to international trade flows and the related emissions embodied in trade with the objective of investigating the ultimate drivers of emissions. The proposed accounting approach is meant to complement existing production-based accounting approaches by identifying potential entry points for mitigation strategies that focus on consumption-driven dynamics such as international trade. An analysis is also performed to reveal the interlinkages between the international trade of dairy products and food security (FAO et al., 2024) in countries where imports are particularly relevant to highlight the positive role dairy exporters play in promoting global food security through trade. This paper provides a novel allocation of the global environmental impact of dairy cattle, thus addressing policies aimed at reducing GHG emissions from this relevant sector by using a new perspective. Therefore, the ultimate aim of this paper is to reduce the knowledge gap between science and policy.

2. Methodology

2.1. Production and consumption emissions

Our analysis is divided into two parts, corresponding to the production phase and the consumption phase. The analysis covers global dairy production at country scale, including 254 territories as defined by the ISO3 code used by FAO (FAOSTAT, 2025) (see Table S1 for details), only focusing on dairy cattle products — thus excluding buffalo, sheep, and other species farmed for milk production. Following the GLEAM approach (FAO, 2023a), GHG emissions were allocated based on country-specific estimates of the protein content of meat and milk produced from dairy cattle farming. Details can be found in Figure S1 in the *supplementary material*. A base year of 2015 was chosen based on data availability; the related data were retrieved from FAOSTAT (2025) for the same year. Although between 2015 and 2022 global dairy production increased by 13% (FAOSTAT, 2025), the increase was mostly homogeneous across countries, with the only exception of India and Germany, whose production relevance increased by 5.6% and decreased by 3.8%, respectively over the global production, while no variation larger than 1% was recorded for any other analysed country (FAOSTAT, 2025). Similarly, over the same period dairy consumption levels increased homogeneously across countries, with the only exception of India and the U.S., whose consumption relevance increased by 2.8%, and decreased by 1.2% over the global consumption, while no variation larger than 1% was recorded for any other analysed country (FAOSTAT, 2025). Therefore, data for 2015 can be assumed to be still representative.

The production phase includes multiple activities, such as feed production, dairy cattle farming, and dairy processing (Table 1).

Each activity is linked with one or multiple sources of GHG emission. The GHGs considered in the present study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which together account for the vast majority of dairy emissions (FAO and Global Dairy Platform Inc., 2019). The impact on climate change of the assessed GHG emissions was estimated using the latest available global warming potentials over 100 years (GWP_{100}) for each gas (IPCC, 2021). Specifically, CO_2, CH_4, and N_2O were converted into CO_2eq by multiplying their value by 1, 27, and 273, respectively. N_2O and CO_2 emissions are generated during feed production activity as well as during the dairy cattle farming phase, though the latter also generates CH_4 emissions. The dairy products processing phase is linked with CO_2 emissions due to energy use (Table 1). Only feed and fertilizer transport emissions are included. However, post-farm transport emissions and other post-farm emissions (other than the ones linked with processing) are not considered.

The consumption phase considers international trade in dairy products to distinguish between domestic consumption (i.e. consumption in the country of origin of a product), and consumption of imported products. Bilateral trade data for 2015, sourced from FAOSTAT (2025), allowed consumed dairy products to be traced back to the country of production. A schematized representation of the system boundaries is shown in Fig. 1. See Table 1 and Table S2 in the *supplementary material* for a complete overview.

Raw trade data cannot distinguish between direct trade flows and indirect trade flows, namely import and export or re-import and re-export. This poses a challenge to identifying the actual origin of a product imported by a country, as the product may have been traded among different countries before finally being imported by the consumer

Table 1
List of greenhouse gas (GHG) emission sources included in the analysis, including related life cycle phase and activity, specific GHG involved and its global warming potential (GWP).

Phase	Activity	Source	GHG	GWP
Feed production	Fertilizer use	N_2O from fertilizer and crop residues	N_2O	273
Feed production	Fertilizer use	N_2O from manure applied and deposited	N_2O	273
Feed production	Land use change	CO_2 LUC palm kernel cake	CO_2	1
Feed production	Land use change	CO_2 LUC soy	CO_2	1
Feed production	Farming operations for feed production	CO_2 from: - field operations - fertilizer production - pesticide production - processing and transport of feed - blending and pelleting	CO_2	1
Dairy cattle farming	Manure management	N_2O from manure management	N_2O	273
Dairy cattle farming	Manure management	CH_4 from manure management	CH_4	27
Dairy cattle farming	Enteric fermentation	CH_4 from enteric fermentation	CH_4	27
Dairy cattle farming	Energy use	CO_2 from direct energy use	CO_2	1
Dairy cattle farming	Energy use	CO_2 from indirect energy use	CO_2	1
Processing	Energy use	CO_2 from energy use in processing	CO_2	1

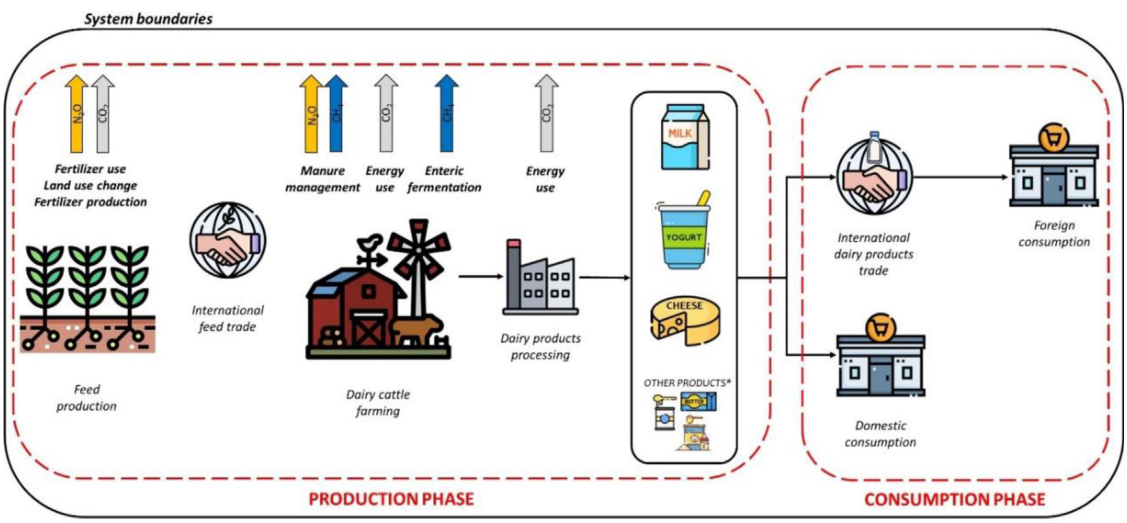

Fig. 1. Schematic diagram of the system boundaries of the studied system showing phases, activities, sources, and related GHG emissions.

country. This so-called "Rotterdam effect"[1] may result, for example, in attribution of the origin of an export flow of a commodity to a country where such a commodity is not even produced (e.g., palm oil from non-tropical countries). To overcome this issue and ensure that the considered trade flows reflect the actual countries of production and consumption, raw bilateral trade data must be first processed. In an approach developed by Kastner et al. (2011), export flows are constrained by the production volumes of each producing country, thus ensuring there is no export flow attributed to countries without production. The present analysis focuses not only on fresh milk, but also on various dairy products such as cheese, butter, and yogurt (see Table S3 in the *supplementary material*). Overall, 21 dairy cattle commodities are considered in this study. To track the origins of processed products they must be converted into milk equivalents and traced back to the country where the milk was originally produced. In our study, the conversion was done in physical terms, considering the mass balance of the various production processes (see Table S3). However, conversions purely based on mass can lead to double counting. For instance, if producing 0.2 kg of cheese from skimmed milk requires 1 kg of whole milk, producing 0.1 kg of cream requires 1 kg of whole milk. Converting 0.2 kg of cheese and 0.1 kg of cream back into whole milk would result in 2 kg of whole milk, but 1 kg of milk yields both 0.2 kg of cheese from skimmed milk and 0.1 kg of cream. A direct conversion could therefore lead to double counting. To avoid such an issue, an economic allocation was applied, ensuring that the consistency of the conversion is maintained following the proportion of economic value attributable to the different dairy products (see Table S3) (Sporchia et al., 2021a, 2023). Mass and value conversion factors were retrieved from FAO (1997), the Water Footprint Network (Mekonnen and Hoekstra, 2010), or estimated combining them according to specific industrial processes (Tetra Pak, 2015). Wherever no information was available on the species of livestock producing the milk used for processed dairy products, the livestock species of origin was assumed to be cattle.

While backtracking the origin of milk represents an important step for correctly assigning consumption-based environmental impacts, the feed used in the dairy cattle farming may also have been imported by the milk producing country. In this case, however, no trade data processing was required since the emission data for dairy cattle farming had already accounted for the origin of the feed. Therefore, the present analysis captures the impacts of the feed production required for dairy cattle farming, whether domestically sourced or imported. Emission intensities were calculated from data retrieved from GLEAM-i, an interactive tool made available by FAO (FAO, 2023a) to estimate livestock emissions. GLEAM-i is an open-access version of the global livestock environmental assessment model (GLEAM), which calculates Tier 2 GHG emissions for individual animal cohorts (FAO, 2023b).

[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_statistics_-_background#Data_collection.

Since the present analysis aims to cover all kinds of dairy products, GHG emissions generated during processing (e.g., to obtain yogurt, cheese, and butter) must also be accounted for. Accordingly, we collected product-specific GHG emission intensities from Ecoinvent (2023). Ecoinvent does not provide country specific values, therefore we assumed global values to be representative for all countries. For the dairy processing phase, CO_2 production from energy use was the only significant GHG emission, so the only one included. Details on the selected product-specific process can be found in Table S3.

Once the intensities have been calculated for each source, for each GHG, for each activity, and for each country (from field to farm gate), they were applied to the milk production of each country. Milk production data were retrieved from FAOSTAT (2025) and represented the basis for the calculation of the emission from production as shown in Eq. (1):

$$MPBA_c = \sum_{a,s,g}^{M} P_c \cdot I_{c,a,s,g} \quad (1)$$

where *MPBA* represents the production-based accounting emissions for milk production in country *c*, *MP* indicates the milk production in country *c*, and *I* is the emission intensity of country *c*, for activity *a*, source *s*, and GHG *g*. This operation gives the first component of the GHG emission of the production phase.

The second component of the production-based accounting emission comprises emissions due to dairy processing. They were estimated at country level starting from country-specific production data for processed dairy products retrieved from FAOSTAT (2025). The GHG emissions were calculated using Eq. (2):

$$PDPBA_c = \sum_{p}^{P} DP_{c,p} \cdot I_p \quad (2)$$

where *PDPBA* represents the production-based accounting emissions from processed dairy products of country *c*, *PDP* indicates the production of the processed dairy product *p* in country *c*, and *I* indicates the emission intensity for processed dairy product *p*. This operation provides the second component of the GHG emission of the production phase. Note that there is no distinction between different GHG as only CO_2 is considered in this phase, being it the only GHG emitted, due to energy use. The sum of *MPBA* and *PDPBA* provides the total production-based accounting GHG emissions linked to dairy production.

Consumption-based accounting GHG emissions are calculated as the balance between production and trade as follows in Eq. (3):

$$CBA_c = PBA_c + EEI_c - EEE_c \quad (3)$$

where *CBA* represents consumption-based accounting emissions from dairy products, *PBA* indicates the production-based accounting emission from production of dairy products (milk and processed dairy) for country *c*, *EEI* indicates the emissions embodied in the dairy products imported by country *c*, calculated as follows, using Eq. (4):

$$EEI_c = \sum_{e \neq c}^{M} I_{c,e} \cdot I_e \quad (4)$$

where *MI* is the quantity of milk (equivalent) imported by country *c* from exporting country *e* and *I* is the emission intensity of exporting country *e*.

EEE in Eq. (3) represents the GHG emissions embodied in the dairy products exported by country *c*, and is calculated using Eq. (5):

$$EEE_c = \sum_{i \neq c}^{M} E_{c,i} \cdot I_c \quad (5)$$

where *ME* indicates the quantity of milk (equivalent) exported by country *c* to importing country *i* and *I* is the emission intensity of exporting country *c*.

EEI and *EEE* are estimated by applying the GHG emission intensity of the country of origin to the flows of direct import and direct export, respectively. The calculation is based on the concept of apparent consumption which is commonly used in the study of international trade and its effects (Sporchia et al., 2021b). This data elaboration process ensures that import and export are correctly tracked and that the applied intensities reflect the actual origin of the traded commodities, avoiding possible distortions due to re-export and re-import flows. *EEI* and *EEE* are collectively referred to as Emission Embodied in Trade (EET) (Sporchia et al., 2021b) and their calculation allows a distinction to be made between net importers and net exporters of emissions. Countries for which *EEI* is larger than *EEE* are net importers of emissions, whereas countries for which *EEI* is lower than *EEE* are net exporters of emissions (Caro et al., 2017).

2.2. Links between global dairy trade and food security

In countries where dairy products contribute significantly to providing fundamental nutrients (e.g., protein and fat) (FAOSTAT, 2025), there may be important links between global dairy trade and food security. By mapping the import trade flows and comparing them with consumption levels it is possible, for each of these countries, to investigate the relevance of the dairy products imported in relation to overall dairy consumption. This can reveal essential interconnection between exporting countries and food security in importing countries.

To investigate the links between dairy trade and food security, we combined trade flows and consumption levels estimated to infer the relevance of the import flows from specific exporting countries over the consumption levels of countries relying heavily on imports. The relevance of dairy on the nutritional supply of countries was estimated based on data retrieved from the FAO Food Balance Sheet (FAOSTAT, 2025), and focused on fat, protein, and energy supply. FAO Food Balance Sheet provides annual country-level information about food and nutrients supply such as food supply quantity (kcal), protein supply (t), and fat supply (t) for a series of food items or aggregate food items. For the present analysis the items "Milk — Excluding Butter" and "Butter, Ghee" were included to capture all types of dairy products. The reliance of a country on import from a specific provider was calculated as the ratio between the dairy products imported from such supplier over the total consumption of such country.

3. Results

3.1. Production and consumption emissions

Our assessment reveals that in 2015, global (254 territories) dairy cattle production released about 1496 Mt of CO_2eq into the atmosphere. Of these, 52% were due to CH_4 from enteric fermentation (777 Mt of CO_2eq). Other relevant sources of GHG emissions are CO_2 emissions arising from feed production (200 Mt of CO_2eq, 13%) and N_2O emissions from fertilizer and crop residues (129 Mt of CO_2eq, 9%) and from manure applied and deposited (122 Mt of CO_2eq, 8%). CH_4 and N_2O emissions were also produced from manure management (96 Mt of CO_2eq, 6% and 56 Mt of CO_2eq, 4%, respectively) and CO_2 emissions from processing (44 Mt of CO_2eq, 3%). CO_2 emissions from energy use and other feed-related emissions are negligible.

India was the largest producer of dairy cattle emissions (246 Mt of CO_2eq) followed by U.S. (135 Mt of CO_2eq) and Brazil (128 Mt of CO_2eq). China, Pakistan, and Russia follow these, with 74 Mt CO_2eq, 61 Mt CO_2eq, and 52 Mt CO_2eq, respectively. Other major producers were Germany, New Zealand, and France. It is important to note that countries differ considerably in terms of GHG type and GHG emission source, due largely to differences in feed and farming practices — see *supplementary material* and Figure S2 for further details. This variety affects not only the GHG emissions profile from a production viewpoint, but also the GHG emission profile from a consumption viewpoint.

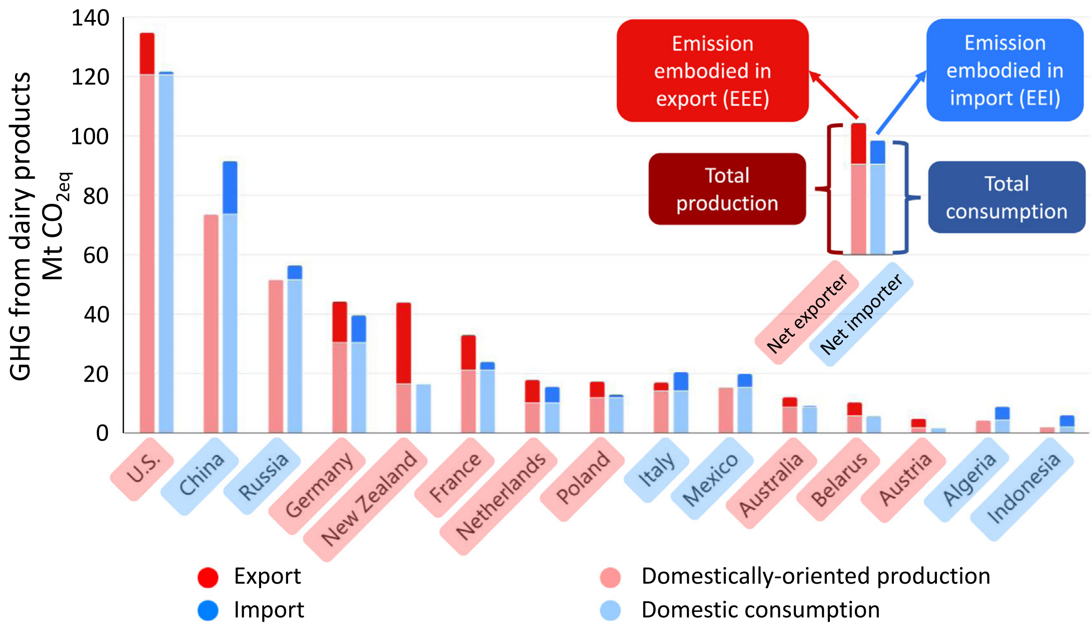

Fig. 2. Comparison between production- and consumption-based accounting for the 15 countries with the highest absolute emissions embodied in trade (EET) of dairy products at the global level in 2015. Both the emission embodied in export (EEE) and in import (EEI) are shown. Net exporters are highlighted in red while net importers are highlighted in blue. Emissions are expressed as Mt of CO_2eq. Countries are sorted by total production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In terms of consumption of dairy cattle products in 2015, India (246 Mt of CO_2eq), Brazil (128 Mt of CO_2eq), and U.S. (122 Mt of CO_2eq) were the countries with the largest emissions, followed by China (91 Mt of CO_2eq), Pakistan (61 Mt of CO_2eq), and Russia (57 Mt of CO_2eq). While the ranking is the same as for production-based emissions, the differences between production- and consumption-based emissions is small for some countries (e.g. zero for Brazil) but large for other countries, most notably China and Russia.

133 Mt of CO_2eq emissions were related to dairy products produced in one country and consumed in a different one, meaning that about 9% of global dairy cattle emissions were embodied in traded goods. By comparing production- with consumption-based accounting it is possible to distinguish countries that are net importers (*EEI* is larger than *EEE*) from those that are net exporters (*EEI* is lower than *EEE*) of emissions. Whilst 9% may not seem a great deal at the global level, the importance of embodied emissions is highly significant for some countries. For instance, emission embodied in dairy cattle products imported by China (18 Mt of CO_2eq) was 20% of the total emissions due to Chinese consumption (91 Mt of CO_2eq, Fig. 2). Conversely, U.S. was a net exporter of emissions, with those due to consumption of dairy cattle products (122 Mt of CO_2eq) lower than those arising from domestic production (135 Mt of CO_2eq). *EEE* accounted for 10% (14 Mt of CO_2eq) of the latter. New Zealand showed a large difference between production- (44 Mt of CO_2eq) and consumption- (17 Mt of CO_2eq) based accounting, and was a net exporter, with *EEE* accounting for 63% of its total production (Fig. 2). Germany, France, Argentina and the Netherlands were also net exporters, although the differences between production- and consumption-based accounting were less marked for them. Russia, Italy and Mexico were net importers of dairy emissions (Fig. 2).

Fig. 3 provides an expanded view of the traded portions of the emissions shown in Fig. 2. New Zealand exported 28 Mt of CO_2eq of *EEE* in 2015 (red bar in Fig. 3). U.S., Germany and France were also significant exporters, with 14, 14 and 12 Mt of CO_2eq of *EEE*, respectively (Fig. 3). In the same year, China imported 18 Mt of CO_2eq of *EEI* (Fig. 3). For some countries, imports and exports are heavily biased towards one or the other. Algeria, Indonesia, China, Mexico and Russia, for example, were importers with low levels of reciprocal trade. Conversely, New Zealand and U.S. exported dairy emissions and imported virtually nothing. However, Fig. 3 shows that some countries, such as Italy, the Netherlands, France and Germany, recorded high levels of embodied emissions due to both imports and exports. For instance, Germany exported 14 Mt of CO_2eq but also imported 9 Mt of CO_2eq (with net of 5 Mt of CO_2eq exported). Netherlands and Italy exported 8 and 3 Mt of CO_2eq of *EEI*, respectively, but also imported about 6 Mt of CO_2eq each (Fig. 3).

Considering bilateral flows of traded emissions between countries (Fig. 4), it is evident that the largest flow of *EET* was the export from New Zealand to China (8 Mt of CO_2eq). The export of emissions from Belarus to Russia (4.5 Mt of CO_2eq) and from U.S. to China (4 Mt of CO_2eq) and to Mexico (4 Mt of CO_2eq) were also considerable flows. Among European countries Germany was the main actor as both importer and exporter. A substantial flow from Germany to Italy and to Netherlands (both around 2 Mt of CO_2eq) was recorded together with a considerable flow from Austria (2 Mt of CO_2eq) and France (1 Mt of CO_2eq) to Germany, while at the same time France exported 1 Mt of CO_2eq to Italy. As well as exporting to China New Zealand exported considerable amounts of emissions to Algeria (2 Mt of CO_2eq) and to other South East Asian countries, such as Malaysia, Indonesia and Thailand (each about 1 Mt of CO_2eq).

Broadly speaking, the countries with the highest GHG emissions due to dairy product consumption are those most populous, but in per capita terms the global picture changes considerably (Fig. S3 see *supplementary materials*). Indeed, countries belonging to Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) recorded the highest per capita GHG emissions linked with the consumption of dairy cattle products, reaching an average of 0.79 t CO_2eq per capita in 2015. The high per capita emissions in Central Asia result from extremely high per capita dairy consumption (409 kcal/(cap day) (FAOSTAT, 2025), combined with production emission intensities that are slightly below the global average (with the exception of Tajikistan, where they are notably higher), and an industry primarily focused on domestic markets. Southern African countries (Botswana, Lesotho, Namibia, Eswatini, and South Africa) followed, averaging 0.54 t CO_2eq

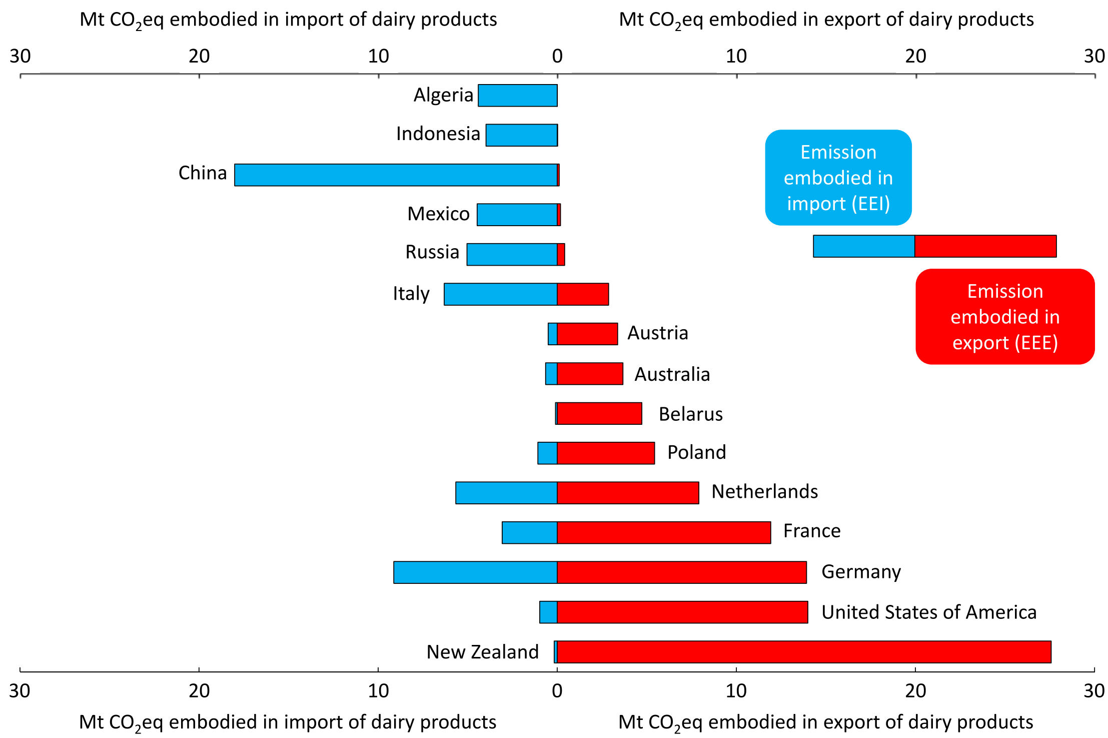

Fig. 3. Balance emissions embodied in imports (EEI) and exports (EEE) of dairy cattle products relative to the largest 15 net importing/exporting countries in 2015. Emissions are expressed as Mt of CO_2 *eq*. Countries are sorted by EEE.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

per capita. Europe (0.48, 0.40, 0.32, and 0.29 t CO_2eq per capita for Northern, Western, Eastern, and Southern Europe, respectively) followed together with Central American countries (Belize, Costa Rica, Guatemala, Honduras, Mexico, Nicaragua, Panamá, and El Salvador with 0.34 t CO_2eq per capita on average) and South American ones (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, French Guyana, Guyana, Perú, Paraguay, Suriname, Uruguay, and Venezuela) with 0.28 t CO_2eq per capita, on average in 2015. The differences among the rest of the analysed areas are less relevant and there are no evident trends such as the one identified for European countries (Fig. S3).

When global emissions from the production and consumption of dairy products are aggregated between developed and developing countries (Fig. 5), a weak shift of emissions is observed. While 64% of global GHG emissions from dairy products are linked with production in developing countries, consumption-based accounting attributes 68% of the total to them, with a 4% shift from developed to developing countries.

Looking at the underlying physical flows (in mass of milk equivalents) utilized for the emission calculation, developing countries account for 44% of global production of dairy products, and 50% of consumption, while developed countries account for 93% of the global export of dairy products, but only 45% of global dairy products imports. This indicates that, in general, developing countries have higher emission intensities than developed countries.

3.2. Linkages of global dairy trade with food security

It is important to note the major role played by international trade for food security in importing countries. Although the export of dairy products from top exporters such as France, Netherlands, New Zealand, and United States accounts for most of the emissions embodied in trade (Figs. 2, 3), these flows represent significant proportions of the supply of nutrients in several of their trade partners. Table 2 provides some statistics for selected countries that rely heavily (15% or more) on imports to make up their levels of milk consumption.

In these countries, imported dairy products make considerable contributions to nutrition in terms of protein, fat, and energy. Most of these are developing countries. For instance, according to FAOSTAT data, in Guyana, Jamaica, Djibouti, Libya, Algeria, Jordan, and Belize out of a daily per capita supply of protein reaching 102, 84, 78, 96, 95, 76, and 76 g of protein, 16, 8, 8, 12, 15, 8, and 7 g of protein are supplied by dairy products, respectively. For the same countries, out of a daily per capita supply of fat reaching 54, 79, 62, 98, 98, 92, and 74 g of fat, 14, 10, 8, 12, 15, 8, and 7 g of fat are supplied by dairy products, respectively. Finally, out of a daily per capita supply of energy reaching 3017, 2831, 2758, 3131, 3425, 2807, and 2719 kcal, 276, 172, 145, 221, 280, 135, and 125 kcal are supplied by dairy products. Delving deeper into the results shown in Fig. 5, physical trade flows (in mass of milk equivalents) highlighted a defined flow direction where developing importing countries imported 88% of dairy products from developed countries, and developed countries directed 51% of their export of dairy products to developing countries (Table 3).

Instead, developed countries accounted for just 7% of the destination of the export of dairy products from developing countries and developing countries covered 1% only of the origin of the dairy products imported by developing countries (Table 3). Considering that a significant part of the food supply is lost after reaching the retail phase (5%–36% Cederberg and Sonesson, 2011) and that the overall "farm-to-fork" food waste accounts for about one third of the food production (Cederberg and Sonesson, 2011), it is possible to estimate the actual energy intake from the supply (retail phase, Table 2) by excluding the post-retail losses, and compare it to the recommended energy intake for adults (average male and female, about 2550 kcal/cap/day) (US National Research Council, 1989). This highlights that most of the countries listed in Table 2 have average per capita daily energy intake lower than the recommended levels for adults.

3.3. Regional trends

The high level of production and consumption in the European Union (EU) makes the EU a hotspot of international trade of dairy

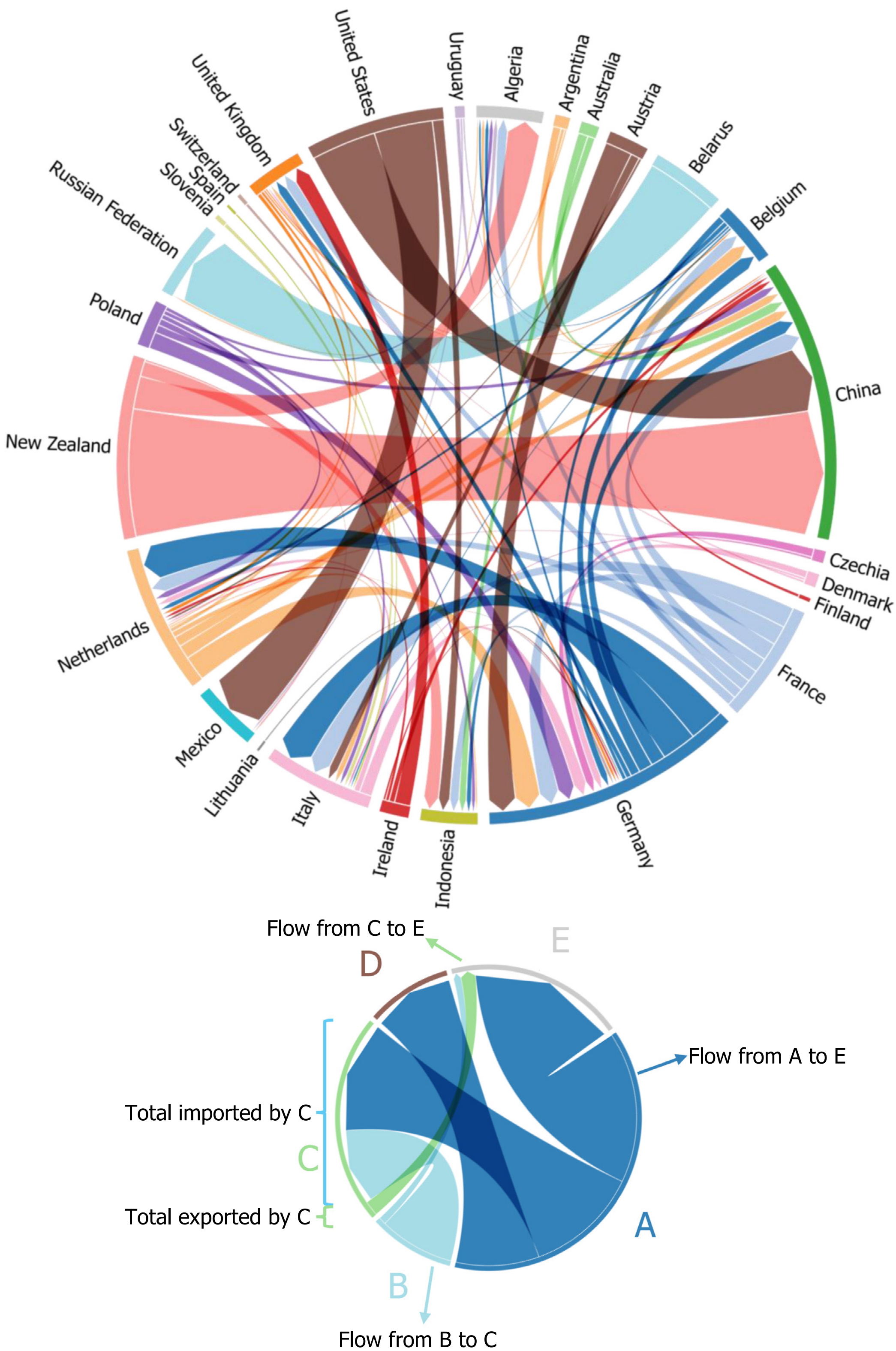

Fig. 4. Top bilateral flows of emissions embodied in international trade of dairy products among the major exporting and importing countries. The size of each flow shows its relevance, and its colour coincides with the country of origin, indicated by the circles next to the country names. The size of each flow shown is in proportion to the related GHG emission value. Only flows to the top 10 importing countries are shown. Only the flows covering at least 2% of the total import from such countries are shown.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

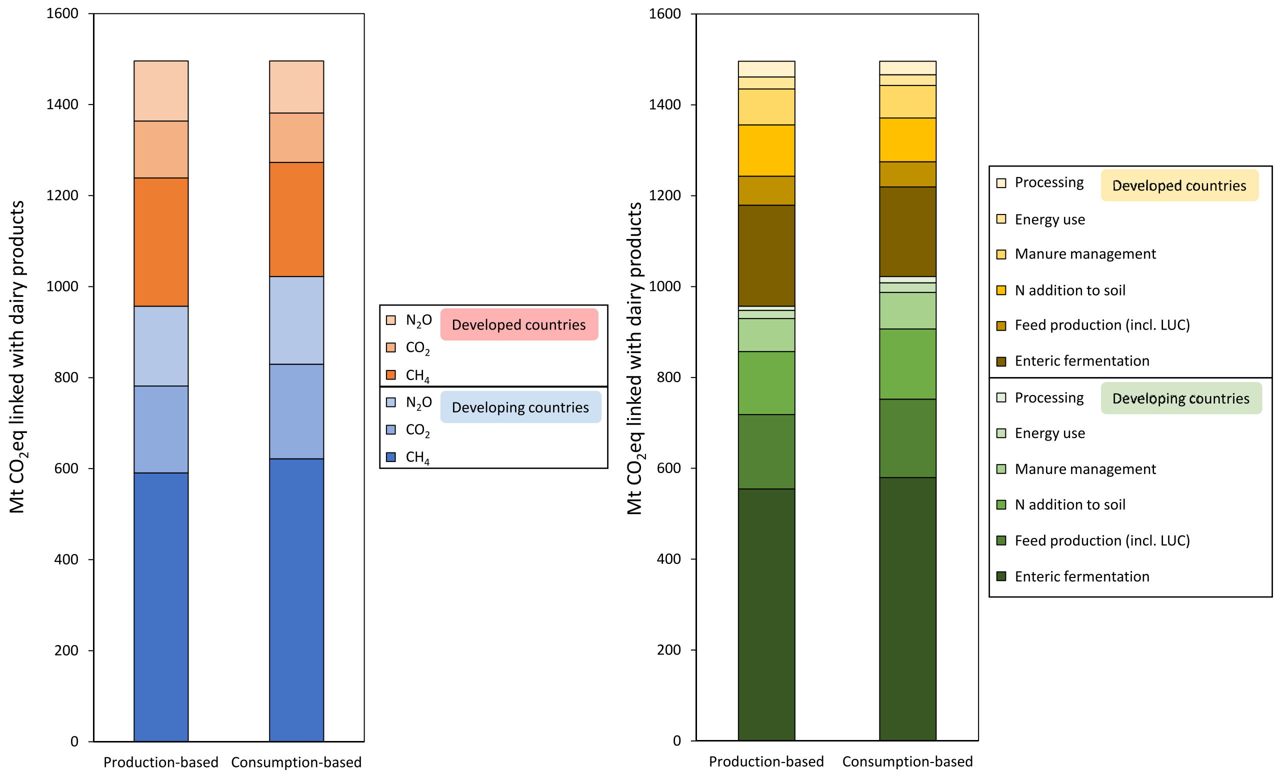

Fig. 5. Comparison between the global dairy products-related emission breakdown by GHG and by source (aggregated) calculated according to the production-based accounting and the consumption-based accounting. Developed countries are here identified as Annex I Parties including the industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including Russia, the Baltic States, and several Central and Eastern European States.

Table 2
The reliance of consuming countries on the import from the top exporting countries, in terms of mass of milk equivalent. The relevance of dairy products over the national supply of protein, fat, energy, and daily energy per capita (FAOSTAT, 2025) for the consuming countries is shown in the right columns. A cut-off was applied to show only couples of countries for which the reliance is higher than 15%, at least one of the three nutritional aspects is higher than 10%.

Import origin	Consuming (importing) country	Reliance on import from origin	Protein	Fat	Energy	Food supply (kcal/cap/day)
France	French Polynesia	42%	8%	16%	9%	2826
France	New Caledonia	37%	11%	16%	8%	2778
France	Luxembourg	27%	22%	23%	14%	3380
Netherlands	Grenada	17%	9%	10%	6%	2410
Netherlands	Antigua and Barbuda	16%	9%	15%	9%	2410
New Zealand	Mauritius	13%	12%	9%	6%	2969
New Zealand	New Caledonia	13%	11%	16%	8%	2778
New Zealand	United Arab Emirates	12%	11%	10%	8%	3190
New Zealand	Barbados	11%	10%	13%	7%	3088
New Zealand	French Polynesia	11%	8%	16%	9%	2826
New Zealand	Guyana	11%	16%	25%	9%	3017
New Zealand	Oman	11%	18%	25%	11%	3050
New Zealand	Jamaica	11%	10%	13%	6%	2831
New Zealand	Maldives	9%	8%	22%	10%	2702
New Zealand	Trinidad and Tobago	9%	10%	10%	6%	2982
New Zealand	Djibouti	9%	10%	12%	5%	2758
New Zealand	Libya	8%	13%	12%	7%	3131
New Zealand	Algeria	8%	16%	15%	8%	3425
New Zealand	Saudi Arabia	8%	10%	12%	6%	3202
New Zealand	Kuwait	8%	14%	18%	8%	3475
New Zealand	Saint Lucia	8%	9%	13%	6%	2602
New Zealand	Jordan	7%	10%	8%	5%	2807
United States	Bahamas	7%	9%	14%	7%	2545
United States	Saint Kitts and Nevis	7%	10%	11%	9%	2746
United States	Jamaica	7%	10%	13%	6%	2831
United States	Mexico	7%	10%	11%	6%	3196
United States	Belize	6%	9%	10%	5%	2704
United States	Antigua and Barbuda	6%	9%	15%	9%	2410
United States	Saint Vincent and the Grenadines	6%	8%	10%	5%	3030
United States	Barbados	6%	10%	13%	7%	3088

Table 3
Breakdown of the physical flows of international trade of dairy products by countries classification for exporters and importers. Figures are provided in absolute mass units (Mt of milk equivalents) and as percentage relative to the total import and export flow.

			Exporter				Total import	
			Developed countries		Developing countries		Mt milk eq	% over import
			Mt milk eq	% over import	Mt milk eq	% over import		
Importer	Developed countries	Mt milk eq	39.31	98.99%	0.40	1.01%	**39.71**	100%
		% over export	48.13%	–	6.65%	–	–	
	Developing countries	Mt milk eq	42.35	88.22%	5.66	11.78%	**48.01**	100%
		% over export	51.87%	–	93.35%	–	–	
Total export		Mt milk eq	**81.66**	–	**6.06**		–	
		% over export	**100%**		**100%**			

products and related GHG emission. The case of EU is here used to show the potential of the adopted approach to investigate regional dynamics beside global ones. In 2015 the trade among 28 member states of the EU was linked with 32% of the global GHG emission linked with the international trade of dairy products, and 36% in physical terms (mass of milk equivalent). All countries were engaged in the import and export of GHG emission linked with dairy products, although differently. The top five countries by GHG emission embodied in intra-EU import were Germany (8 Mt CO_2eq, 21% of the total), Italy (6 Mt CO_2eq, 15% of the total), the Netherlands (5 Mt CO_2eq, 13% of the total), the U.K. (3 Mt CO_2eq, 8% of the total), and Belgium (3 Mt CO_2eq, 7% of the total). In terms of import the top 5 countries were Germany (9 Mt CO_2eq, 23% of the total), France (6 Mt CO_2eq, 16% of the total), the Netherlands (4 Mt CO_2eq, 11% of the total), Poland (3 Mt CO_2eq, 7% of the total), and Austria (2 Mt CO_2eq, 6% of the total). As shown in Fig. 6, trade flows are in many cases bilateral, meaning that couples of countries are engaged in trade with each other in both directions.

For instance, the export of dairy products from Germany to Belgium was linked with 810 kt CO_2eq, but Germany in turn imported dairy products from Belgium too, the latter being linked with 428 kt CO_2eq (Fig. 6). A similar case involves the U.K, and Ireland, with the first exported dairy products to the latter linked with 918 kt CO_2eq. In turn, Ireland exported 749 kt CO_2eq embodied in dairy products to the U.K (Fig. 6).

4. Discussion

4.1. Global overview and regional hotspots

Our analysis found that in 2015 global (254 territories) dairy cattle production was responsible for about 1502 Mt of CO_2eq emissions, fully in line with previous FAO estimates (FAO and Global Dairy Platform Inc. (2019) estimated 1711.8 Mt CO_2eq but calculated with older GWP values for N_2O and CH_4, with which our analysis would reach 1706.5 CO_2eq). The study highlighted that more than half of global dairy cattle emissions were due to CH_4 emissions from enteric fermentation. Mitigating this important source of emissions is of primary importance in the fight against climate change. Several effective CH_4 mitigation practices are available for the livestock sector (Beauchemin et al., 2022; FAO, 2023c; Herrero et al., 2016; Hristov et al., 2013; Kebreab et al., 2023; Monteiro et al., 2024) and this analysis shows that actions in dairy producing countries can directly affect trade-related emissions. Besides mitigating actions directly targeting the milk production phase where N_2O and CH_4 dominate emissions, it is important also to target the processing phase. In this phase, CO_2 is the most important GHG, especially for countries exporting mostly processed dairy products. In New Zealand, for example, the largest exporter of GHG emissions (Fig. 3), CO_2 from processing (Figure S2) accounts for 17% of the total GHG emissions, highlighting the relevance of post-farm GHG emission along certain agricultural supply chains (Tubiello et al., 2022). Accordingly, reducing GHG emissions linked to processing raw milk in New Zealand could play a key role in cutting global dairy cattle emissions, both from domestic and foreign consumption.

Although at the global level the emissions embodied in trade of dairy cattle products accounted for just 9% of global dairy cattle emissions, our analysis shows that for countries heavily involved in trade, these emissions can be very important (Fig. 2). We revealed how, in such cases, dairy consumption and the related environmental burden are telecoupled (Busck-Lumholt et al., 2022; Munroe et al., 2019). Our findings confirm how the international trade of dairy products is dominated by as few as the largest 20 net importing/exporting countries. These countries cover about 70% of global emissions embodied in the trade of these products. Our analysis highlights that emission intensities vary regionally (Figure S1) and identifies entry points for effective regional and national policies regulating livestock emissions that currently overlook the role of trade. For example, the consumption-based analysis presented here can be used to define GHG-based border adjustment taxes such as the ones currently discussed and implemented (on cement, iron and steel, aluminium, fertilizers, and electricity) in the European Union (EU) (European Parliament, 2023). Moreover, it may encourage the shift to low-carbon dairy products, more efficient use of resources, and the promotion of circular economy models, thereby reducing global demand for high-emission goods. Furthermore, by tracking emissions based on consumption patterns, policymakers can identify where the largest impacts are occurring throughout all stages of the supply chain (Fig. 1) and focus climate policies and interventions where they are most effective in reducing emissions.

The largest net effect of global dairy trade relates to exports from New Zealand to consumers in China and from U.S. to China and Mexico (Fig. 4). China is the largest importer of emissions with large amounts of emissions released in other countries to satisfy Chinese demand. While 20 years ago most dairy farms in China were small and family-owned and China's consumption was covered by just importing products from elsewhere, these farms are being replaced by much bigger farms, sometimes raising tens of thousands of dairy cows, and this has allowed a quadrupling of Chinese domestic dairy consumption between 2001 and 2023 (USDA, 2023, 2002). Nevertheless, China livestock farming faces sustainability challenges. For instance, only 43% of manure is applied to the cropland, while most is discarded (Gu et al., 2015) generating a substantial amount of avoidable GHG emissions. Furthermore, China's milk production is highly concentrated and primarily based in the Northern part of the country (Zhuang et al., 2020) with environmental impacts due to concentration, and high levels of internal trade. Dairy cattle populations in China tripled between 2000 and 2015 (China Agricultural Statistical Yearbook, 2016) driven by domestic demand. Nevertheless, China is expected to remain the largest importer of milk products (Fuller et al., 2006; Wang et al., 2021), and domestic production is forecast to continue facing sustainability challenges (Han et al., 2024). China, together with other large importers, represents a major entry point for national and international policies aimed to mitigate GHG emission – a global issue — through collective actions. This calls for strategies scoping beyond national territorial borders (and jurisdiction), that account for responsibility for environmental burdens regardless of their point of generation. This is

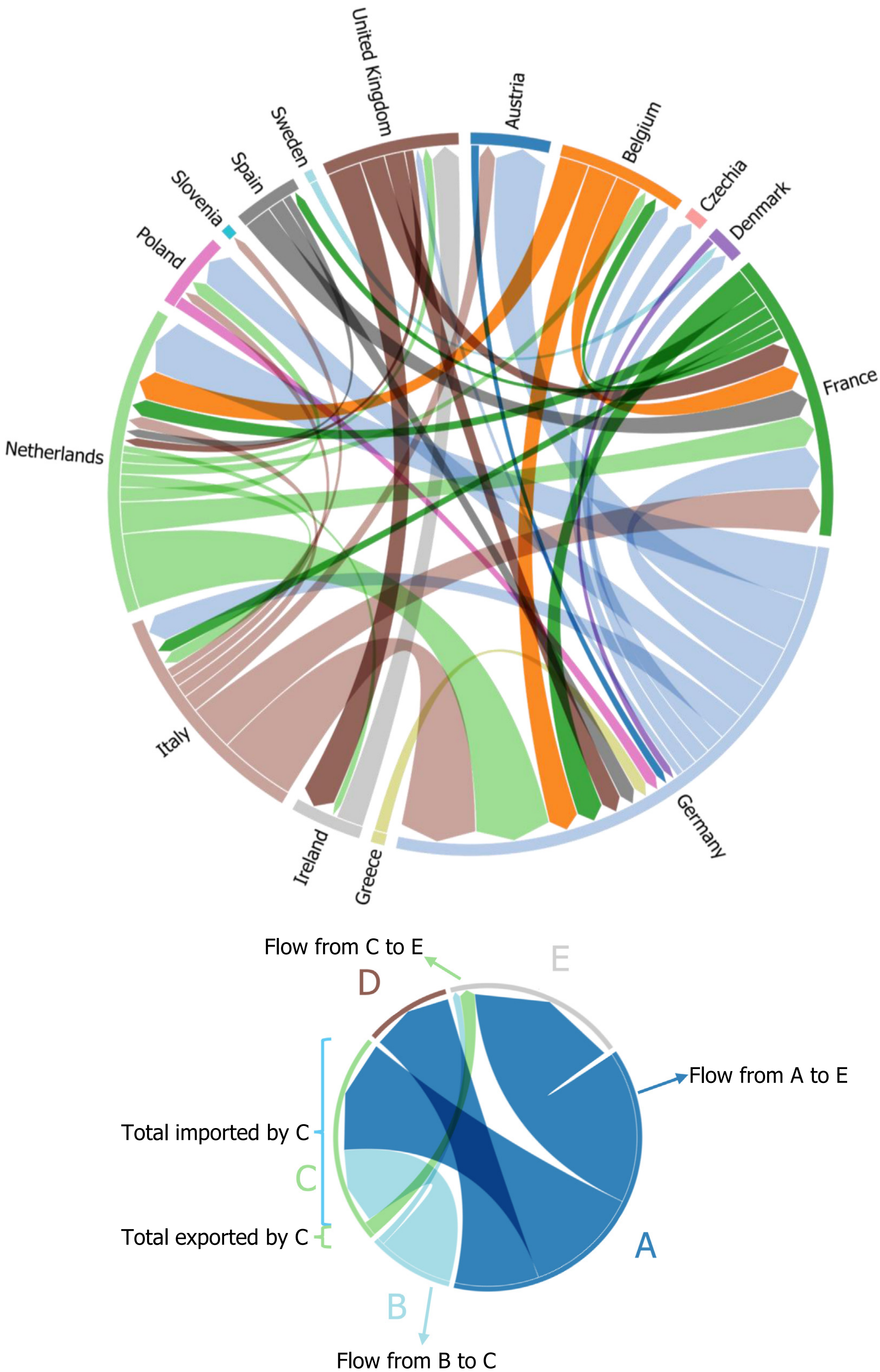

Fig. 6. Top bilateral flows of emissions embodied in intra-EU international trade of dairy products. The size of each flow shows its relevance, and its colour coincides with the country of origin, indicated by the circles next to the country names. The size of each flow shown is in proportion to the related GHG emission value. Only trade flows covering at least 0.5% of the total intra-EU emission embodied in the trade of dairy products.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

particularly important as climate crisis is affecting, and will continue to affect all countries (although differently) regardless of their past, present, and future role in generating GHG emission.

EU countries such as Germany, Italy, France, and the Netherlands are both importers and exporters of emissions (Fig. 3). This reflects trade liberalization among European countries, unhampered by trade barriers such as tariffs, import or export quotas, and other discriminatory taxes or charges. In the EU the fight against climate change is at the heart of the Green Deal and the Farm to Fork strategy. In this context, trade facilitation is considered to have a key role to play (World Trade Organization, 2022). From one side, trade dynamics are recognized as contributing to GHG emissions (Wang et al., 2023) and sometimes they may hamper the development of a flourishing agricultural sector in many importer countries (Bajaj et al., 2025). From another side, trade enables low-income countries, often with lower per capita agricultural production, meet their nutritional needs, and therefore trade is deemed important for ameliorating the effects of climate change on food security (Eucolait, 2021; Janssens et al., 2020). From this point of view, our analysis can inform policy on trade-related actions to bring down global emissions, for instance, by shifting to more efficient trade partners or identifying the main hotspots.

4.2. Consumption-based accounting versus production-based accounting

Comparison of GHG emissions estimated by production- and consumption-based accounting reveals significant differences, especially for the largest net importing and exporting countries (Fig. 2). The production-based accounting approach commonly applied (IPCC, 2019, 2006) overlooks the effects of production delocalization and international trade, allocating the responsibility for GHG emissions associated with animal products exclusively to the producing countries, regardless of where consumption happens. But our analysis shows the dairy cattle product supply chain to be a telecoupled system (Sun et al., 2017), which poses a challenge for policies that regulate livestock emissions, because national GHG accounting rules neglect emissions embodied in trade (Bastianoni et al., 2014; Caro et al., 2017; Fernández-Amador et al., 2017; Foong et al., 2022). Taking as an example the GHG emissions associated with the large amount of milk produced in New Zealand and then exported to China, should these emissions be allocated to New Zealand as producer country or to China as the consumer country? The present analysis shows how this choice can have a dramatic impact on a country's GHG emission inventory and the associated policy implications. Following present guidelines, the significant flow of emissions embodied in the commodities exported by New Zealand to China (Fig. 4) will not be inventoried in Chinese accounts even though the demand in China is driving to the generation of those emissions in New Zealand. Similarly, these displaced dairy cattle emissions will escape regulation in China, which may encourage further offshoring of livestock operations (i.e. "leakage" OECD, 2021), representing a critical missed opportunity for mitigation. The net trade of dairy cattle-related emissions shown here builds on other evidence for the importance of traded livestock emissions (Balogh and Jámbor, 2020; Caro et al., 2014a; FAO, 2020).

The discussion on how to inventory GHG emissions released from different countries has grown in recent years. If the emission dynamics due to trade globalization are not included in the GHGs accounting framework, we run the risk of misinterpreting the environmental performances of individual countries (Davis and Caldeira, 2010; Foong et al., 2022; Weber et al., 2021). The need to decrease overall GHG emissions may not be fully addressed and incorporated in policies, projects and initiatives (Hong et al., 2022; Karakaya et al., 2019). The current accounting approach for environmental impacts is justified on the basis of national jurisdictions. However, the resource-related risks that countries face extend beyond their national borders offer an important opportunity for resource and environmental management (Chen et al., 2018; Hong et al., 2022).

4.3. The dairy products in the broader context of global food systems

Food systems alone account for about one third of the global anthropogenic impact on climate change. Hence, they should receive priority attention within political agendas (Crippa et al., 2021). It is widely accepted that food consumption and behaviour trends are important drivers of GHG emissions and other environmental burdens (Bruno et al., 2019). Several reports suggest dietary shifts from animal-based foods, including dairy products, to plant-based diets or novel foods are environmentally preferable (Mazac et al., 2022, 2024; Tilman and Clark, 2014). The consumption-based accounting approach presented here would allow the GHG emission impacts of shifting among alternative diets to be explored in detail. It also enables the impact of shifting to alternative sources of the same foods to be evaluated. Traditional production-based accounting approaches fail to deliver on actions of this kind, which may be environmentally beneficial not only nationally (in terms of accounting), but also globally (in terms of overall environmental impact), consisting in changes in imports towards more environmentally sustainable products. Trade in sustainable agricultural products is also relevant for food security (Wood et al., 2018a). Furthermore, reducing consumption of dairy products in a given dairy exporting country will not necessarily correspond to a decrease in its domestic production of milk and dairy products, if exports were simply increased to make up the demand deficit. The real effects of changing consumption patterns can only be captured by consumption-based accounting. Desirable shifts in dietary patterns need be supported by incentives, inclusion of sustainability criteria in national dietary guidelines, public policies, and regulatory changes. Indeed, recent research has remarked the need of stimulating individuals to consume products with lower environmental burdens and higher health and nutritional benefits (Galli et al., 2023; Bruno et al., 2019).

Unlike emissions embodied in most other products (Liu et al., 2022; Wood et al., 2018b), those of dairy products tend to be transferred from developed to developing countries[2] according to the consumption-based accounting approach (Fig. 5). It is notable also that part of the feed is actually produced in developing countries and used by livestock producers in developed countries (Boerema et al., 2016). This highlights the complexity of global dairy supply chains and reveals the peculiar differences and relationships between developing and developed economies.

To further investigate the role of international trade, we designed a hypothetical no-trade 'autarchy' scenario (Wu et al., 2021), where each country maintains the same consumption of dairy cattle products but produces them itself. In this scenario, processing emissions are excluded as they are not affected. At the global level, this autarchic scenario would cause the release of about 1525 Mt of CO_2eq to the atmosphere. Comparing that with the 1452 Mt of CO_2eq associated with the baseline (excluding processing emission), the autarchy scenario would increase global dairy cattle emissions by 5%. This scenario analysis reveals that, in 2015, international trade played an overall positive role in mitigating GHG emissions with respect to a hypothetical autarchic situation. While the global impact may not seem large, the effect of trade can be more important when observed at a country level (see details in the *supplementary material*, Fig. S4). This further demonstrates the capability of consumption-based accounting to capture any country's peculiar supply chain and consumption pattern and provide clear information on opportunities to improve sustainability, as well as to support decision makers in designing trade-related mitigation policies, for example limiting imports in favour of investments in domestic

[2] Developed countries are here identified as Annex I Parties including the industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including Russia, the Baltic States, and several Central and Eastern European States.

efficiency, or switching towards more efficient trade partners while maintaining or reducing domestic production. However, this simulation cannot anticipate complex market effects (Mir, 2015) and it overlooks likely issues related to domestic production capacity for some countries. The analysis assumes the increase in domestic production of importing countries will be at their existing level of efficiency, while in reality such increases may only be sustainable through less sustainable expansion of domestic production. It should be noted that the autarchic scenario here presented is merely a hypothetical and implausible exaggeration of reality, with the sole aim of showing a general trend, rather than providing a specific result, of the role played by international trade (Karakaya et al., 2019). Existing limits in domestic dairy production capacity are strictly connected with countries' food security which, in turn, is linked with international trade. This relationship is particularly evident for some top exporters (Figs. 2, 3, Table 2). The exports from France, the Netherlands, New Zealand, and the US are essential to cover demand for dairy products in some low- and middle-income countries, where dairy products are an essential source of nutrition. The emissions embodied in such exports are therefore necessary to sustain food security in the importing countries, and are likely considerably less than would result from expanding domestic production to meet the same demand, or indeed importing from less efficient producing countries. These exporting countries are among the most efficient in terms of GHG emission intensity (Fig. S1) so redirecting the import flows to other countries would most likely increase GHG emissions overall. Nevertheless, the potential for mitigating global emissions by improving the production efficiency in developing countries such as reducing their emission intensities, should not be underestimated as it would also lead to an overall reduction in GHG emissions. Considering that the process of reporting Nationally Determined Contributions (NDCs) (United Nations, 2015) might put pressure on the major dairy exporters to produce (and export) less, such impositions might have important knock-on effects in importing countries. While substituting dairy with other sources of nutrition might be an option, it is difficult to envision a "silver bullet" substitution that ensures both the safeguard of food security and the reduction of GHG emissions, not only at the national level, but also at the global one.

4.4. Limitations and outlooks

While incorporating the majority of GHG emissions from dairy supply chains, post-farm emission (Tubiello et al., 2022) and those associated with transportation (Li et al., 2022) should ideally be included in future assessments, this will require data that are not currently available. Although our analysis only focuses on GHG emissions, with a special emphasis on international trade of dairy cattle products, the latter are linked with other, equally relevant, environmental issues, in terms of environmental impacts and exploitation of natural resources. These are also embodied in trade flows. For instance, water and land linked to agricultural production are key resources associated with dairy cattle production (including feed) and they are out of the scope of this analysis. Any strategy to reduce the environmental burden of dairy production should therefore recognize the multifaced nature of its impacts (Clark et al., 2019). While our analysis is not a comprehensive impact assessment, it provides a framework for further assessment of impacts and resource use embodied in trade of dairy and indeed other food and agriculture products (Osei-Owusu et al., 2021, 2019). Looking at multiple impacts (Sporchia et al., 2021c) would reduce the possibility of rebound effects: for instance, if GHG emissions were disassociated with the countries they are produced in, this might lead to production increases that could induce negative effects on resource availability. The scope of the study could also be widened to include other relevant social and economic impacts. Another limitation of the study is that it focuses on a single year, 2015. This is due to the fact that most of the input data were retrieved from GLEAM-i (FAO, 2023a), for which the most recent data are from 2015. It would be of considerable benefit to studies such as the present one if international organizations such as FAO were able to provide more contemporaneous data. Restrictions to a single year is also problematic for analyses such as this. For example, 2015 followed a global recession (Goodman and Mance, 2011), which may have had an impact on the analysis. Other events, the COVID-19 pandemic or the war in Ukraine, for example, might distort more usual patterns of trade so it would be beneficial to be able to average data over a series of years for more representative results. The calculations rely on the application of the data processing from by Kastner et al. (2011). The processing procedure is based on the transformation of processed (also called secondary) products in primary products. In this case, products such as butter and cheese are secondary products which are converted into primary raw milk equivalents. This operation is fundamental to properly track international trade flows and thus assign them the proper emission factors. However, this operation incurs a loss of detail about the composition of the consumption of dairy products since this is simply expressed in terms of tons of raw milk. Nevertheless, focus of this work is the application of a consumption-based accounting approach to the dairy sector, the quantification and attribution of GHG emission of the overall dairy is prioritized over the provision of more detailed results at the product-specific level. Further research is needed to obtain more insight into the dairy sector and inform product-specific policies for climate change mitigation.

Another future advancement should focus on the refinement of the processing data, i.e., energy use (heat and electricity). The present analysis utilized global averages as country level data is unavailable. However, the utilized processes rely on diversified sets of energy inputs that would require country-specific modelling rather than a simple substitution (see yogurt production for instance at https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/10778/documentation). The current Ecoinvent database spatial resolution fails to cover all dairy producing countries and using area averages would not necessarily improve the accuracy of global estimates. Regardless, GHG emission from processing covers a marginal part of the overall emissions at the moment, justifying the prioritization of completeness over accuracy. Further research should focus on estimating country-specific energy mixes related to the processes used in the inventory data underlying the emission factors to refine the results of the present analysis. Finally, the distances between countries and transport were not computed in the estimation of the emissions embodied in trade. These drivers are often not considered in traditional consumption-based analyses for several reasons such as difficulty in the attribution and data availability.

Lastly, a shift from production-based accounting to consumption-based accounting may have unintended negative consequences, especially for countries whose domestic dairy production is less efficient than the imports on which they currently rely. On one hand, such countries would get charged with emissions for imports unless they push domestic production – often much less efficient – while exporters get absolved from any emission related to the exported dairy products, meaning that they might respond to any new foreign demand since the related emissions would be transferred. As a consequence, instead of a reduction, an overall global GHG emissions increase could be expected for dairy products. Accordingly, global dairy supply chains could be investigated with an intermediate approach in a future advancement where both producers and consumers are charged for part of the life cycle emissions of products, such as the so called shared responsibility approach (Heidari and Pearce, 2016; Zhang and Pan, 2023). This could allow a more balanced distribution of the mitigation efforts and avoid unintended rebound effects.

5. Conclusions

This study has explored the effects of estimating GHG emissions from dairy cattle systems at the point of consumption rather than of production – i.e. accounting for emissions embedded in trade, including multiple activities, such as feed production, dairy cattle farming, and dairy processing. The analysis delivered an alternative, complementary viewpoint that can provide insights into the impacts of changing production, trade, and consumption patterns. Such information can inform policies and guide activities aimed at sustainably reducing GHG emissions from dairy systems and achieving Sustainable Development Goals (Pradhan et al., 2025). The main objective of a study of this kind is to strengthen the interface between science and policy, which is extremely necessary today (Caro, 2023).

Comparing production- versus consumption-based accounting, we revealed that GHG emissions embodied in international trade of dairy cattle products are 9% globally, but can account for a far greater share at the country level, with embedded emissions accounting for more than 50% of emissions in countries heavily engaged in the trade of milk and dairy products. The study revealed trade patterns for dairy that were quite different from other agricultural commodities, suggesting that the dairy sector requires careful consideration in the climate policy agenda.

The analysis identifies the volume of commodities traded and the national production efficiency (emission intensity) as the main drivers of emissions embodied in trade. The study indicates that reduced consumption of dairy cattle products in some countries could substantially drive down dairy cattle-related GHG emissions in other countries. However, this could have considerable detrimental impacts on food and nutrition security in those countries for which imported milk and dairy products play a crucial role in healthy diets. National policies designed to reduce GHG emissions from dairy systems in countries that export milk and dairy products should also take into consideration the potential impacts of such policies (a) on overall global emissions from dairy systems, and (b) on food and nutrition security.

CRediT authorship contribution statement

D. Caro: Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **F.M. Pulselli:** Writing – review & editing, Validation. **F. Sporchia:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2025.100268.

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