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Analysing the interaction between the dairy sector and climate change from a life cycle perspective: A review

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ABSTRACT

Background: Globally, climate change is a challenge for the dairy sector and its effects are expected to have important consequences on the environmental performance of the dairy products value chains. At the same time, this sector significantly contributes to global warming and other environmental impacts.

Scope and approach: This paper addresses this twin challenge from a life cycle perspective, i.e. covering from dairy farms, dairy factory, distribution and retail, to consumption. To do so, literature reviews were done on the contribution of the sector to climate change and on the biophysical impacts of climate change on the dairy sector in the near term in Europe. Both reviews were linked to qualitatively analyse the interaction and connect in a matrix the biophysical impacts caused by the effects of climate change on the environmental performance of the sector.

Key findings and conclusions: Not surprisingly, dairy farms were identified as the major contributor to the total greenhouse gas emissions across the dairy value chains but also as the most vulnerable stage to climate change. Depending on the region, the dairy sector will face opportunities but also threats such as significant cows' heat stress, crop cultivation variability, on-farm water availability, cows' diseases, crop pests' pressure and product safety risk, which is associated with product losses and waste. Measures will be needed to mitigate them but with an environmental cost. The clear definition of the dairy sector-climate change interaction is the starting point to begin preparing this sector for a near-future under climate change conditions.

1. Introduction

The demand for dairy products is expected to double by 2050 compared to 2000 due to dietary pattern changes, the increment of the global population and the income growth of developing countries (Alexandratos & Bruinsma, 2012). The world population is projected to reach 9.8 billion people by 2050 (Gerber et al., 2013) and consumption patterns of developing countries are projected to shift from staple-based diets to affluent diets, characterized by higher intake of animal commodities as dairy products (Gerbens-Leenes, 2017). Fresh and processed dairy products (i.e. milk, cheese, yoghurt …) are a relevant source of quality nutrients such as calcium, protein, and vitamin D, contributing to a balanced diet Rozenberg et al., 2016. However, their production relies on large amounts of natural resources (i.e. freshwater and arable land) and other inputs (i.e. energy, crops and other materials), resulting in direct and indirect greenhouse gas (GHG) emissions as well as significant contributions to other environmental impacts (Notarnicola, Tassielli, Renzulli, Castellani, & Sala, 2017). IDF, 2015, this sector emitted 1.7 million tonnes of CO_2e, which represents around 3.4% of the total related anthropogenic CO_2e[1] emissions (Olivier, Janssens-Maenhout, Muntean, & Peters, 2016, p. 86) and an increase of 18% compared to 2005, mainly due to higher consumer demand. During the same period, the emission intensities per litre of milk were reduced by 11% thanks to production efficiency improvements. Without them, the emissions from this sector would have increased up to 38% (FAO & GDP, 2018). Within the different greenhouse gases (GHG) involved, methane (CH_4) is the main one representing up to 63.3% of the total carbon footprint of an average dairy product, followed by nitrous oxide (N_2O, up to 24.5%) and carbon dioxide (CO_2, up to 12.2%) (FAO & GDP, 2018). Besides, global warming, water use and water eutrophication

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[1] Carbon oxide equivalent (CO_2e) is a standard unit to compare the radiative forcing of different GHGs to that of CO_2 and it used to express the carbon footprint of a product or service (ISO 14064-1, 2018).

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have also been reported as relevant environmental impacts along the dairy value chains (FAO & GDP, 2018; Gerber et al., 2010).

In order to analyse the contribution to climate change and other environmental impacts of food value chains, Life Cycle Thinking (LCT) is the most suitable approach since it considers the environmental, economic and social impacts of all life cycle stages from farm to consumer (UNEP-SETAC, 2016). Focusing on the environment, Life Cycle Assessment (LCA) is the method used worldwide to quantify the environmental impacts of products and services along their life cycle (ISO 14040, 2006; ISO 14044, 2006). Mass and energy flows (i.e. inputs and outputs) to and from the environment are considered and translated into environmental impact categories. Dairy products are associated with environmental impacts linked to global warming, land use and freshwater eutrophication as well as water depletion (Üçtuğ, 2019) and LCA has been applied to quantify these impacts of a large number of dairy products (Djekic, Miocinovic, Tomasevic, Smigic, & Tomic, 2014; Yan, Humphreys, & Holden, 2011). The Environmental Product Declarations (EPD, 2021) and related Product Category Rules (PCR) on specific dairy products (such as raw milk[2] and processed milk[3]), as well as the Product Environmental Footprint (European Commission, 2012) and related Product Environmental Footprint Category Rules for dairy products,[4] aid to assure a harmonized environmental performance evaluation to ensure comparison and facilitate the communication of results of LCA studies. Individual environmental indicators, such as Carbon Footprint (CF), which quantifies the GHG emissions of products along its life cycle (ISO 14067, 2018), and Water Footprint (WF), which evaluates possible environmental impacts related to water (ISO 14046, 2014), have also been applied to the dairy sector and related products (Noya et al., 2018; Roibás, Martínez, Goris, Barreiro, & Hospido, 2016) and, in this sense, the International Dairy Federation (IDF) has published two documents to provide guidance when calculating both the carbon and water footprints of dairy products (IDF, 2015, 2017).

A global increase in GHG emissions due to anthropogenic activities is the primary cause of climate change, leading to atmospheric warming and having serious implications on the stability of the planet's climate (IPCC, 2014). Climate change has many ways of manifestation: average temperature variation, sea level rise, warming and acidification of oceans, sea ice melting, extreme weather events (i.e. heat waves, droughts, heavy rainfalls), and change in ecosystems (IPCC, 2014). Some of these effects threaten the dairy value chains and will have biophysical impacts on the dairy sector. This might create competition for available resources along its value chains (Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017) and their technical efficiency and environmental performance might be compromised (Key & Sneeringer, 2014). It is known that the rise of temperature is likely to affect the safety of dairy products, by increasing the risk of food spoilage and microbial contamination (FAO, 2020). Also, extreme weather events are likely to occur more frequently and represent a challenge for the productivity of the crops used as animal feeding and on the distribution of harvested land, leading to strong competition for suitable land. Consequently, a modification of the crop trade patterns around the globe might occur (Calzadilla et al., 2013). Besides, in regions susceptible to a significant increment of temperature, cow's performance and health might be influenced, having negative repercussions on their milk production (Fodor et al., 2018). There might not be certainty on the level of those effects will occur, but there is certainty that they will occur and will unevenly threaten the dairy sector depending on its geographic location (European Environment Agency, 2017).

It becomes clear that there is an interaction between the dairy sector and climate change (Fig. 1): on one direction (black arrow), the dairy sector significantly contributes to climate change, besides impacting other environmental categories; while, on the other (grey arrow), the effects of climate change influence the dairy sector, including its value chains, and the associated environmental burdens. In addition, other non-climate stressors (gold arrow) are also expected to influence the dairy sector and could have a significant role in the future; nevertheless, they lie out of the scope of this review since these are external factors that remain out of the direct interaction's control of this study but will be broadly discussed in the last section of this paper.

Therefore, the challenge of the dairy sector is to satisfy the future demand for dairy products under stressful climate conditions while reducing its environmental impact and food safety risks. By giving clear evidence and understanding the dairy sector–climate change interaction, it would be possible to connect vulnerable elements of the dairy value chains with the expected performance change of the dairy value chains. This can support the dairy farmers and the dairy industry in identifying threats but also opportunities, giving rise to efficient and sustainable decision-making to improve the adaptation to the effects of climate change in the near term while reducing their GHG emissions. This paper begins with the description of the review strategy (section 2) to provide, both, an analysis on the contribution of the dairy sector to climate change from a life cycle perspective (section 3); and an assessment of the biophysical impacts of climate change on this sector under the same perspective (section 4). Then, these two analyses are linked to enable a connection of the biophysical impacts of climate change on the environmental performance of the dairy value chains (section 5). Finally, the role of this paper in helping the dairy sector in adapting and facing climate change in the near term is described (section 6).

2. Review strategy

To identify the most relevant literature and to get an overview of both sides of the dairy sector–climate change interaction, a parallel 3-step review strategy was carried out. In one direction, the review focused on the contribution to climate change by the dairy sector across Europe, without ignoring other environmental impacts such as those related to water as they are indirectly connected to GHG emissions. In the other direction, the review looked at the elements of the dairy sector that might be more vulnerable to the climate change effects, possibly influencing its environmental performance.

2.1. System definition

In 2019, the world cow's milk production reached 523 Mt and the

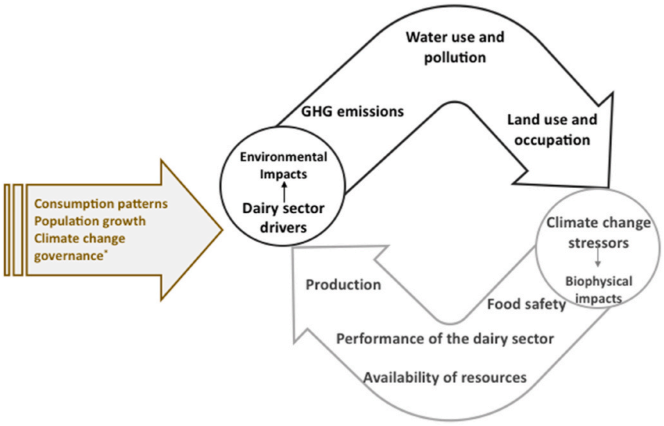

Fig. 1. General overview of the dairy sector – climate change interaction. * Climate change governance refers to the implementation of adaptation and/or mitigation policies, such as energy transition, and strategies.

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[2] PCR, 2013, p. 16 available at https://test1.environdec.com/PCR/Detail/?Pcr=8591, expired in 2020/12/08.

[3] PCR, 2013, p. 17 available at https://test1.environdec.com/PCR/Detail/?Pcr=9261, date of expiration 2021/09/01.

[4] Description and library available at www.ec.europa.eu/environment/eussd/smgp/ef_pilots.htm.

top milk producers were the European Union (EU) (158 Mt), the United States (99 Mt) and India (91 Mt), being the first two also the major dairy exporters and the EU the major cheese producer in the world with 9.5 million tonnes (OECD & FAO, 2020). The abolition of the EU milk quota system in April 2015 has instigated an increase in raw milk production, and thus, dairy products. In the EU, raw milk is mainly used for cheese (38%) and to a lesser extent for butter (29%), cream (12%), liquid milk (11%) and other products such as milk powder and yoghurt (10%) (Eurostat, 2021). Regarding the geographical distribution, milk production within the EU is concentrated in the labelled dairy belt, integrated by Germany (21%), France (16%), United Kingdom (10%), the Netherlands (9%), Poland (8%), and Ireland (5%) and together accounted for 70% of the total European production (Eurostat, 2021).

Every product has its value chain (Fig. 2), which for dairy products is composed of four main stages (Fig. 2a): milk production at dairy farms, processing at the dairy factory, distribution and retail, and final consumption. Across these stages, there are different actors (Fig. 2b) that have a certain capacity to act and/or influence decisions when looking at improving any environmental aspect across the dairy value chain as well as at applying any adaptation strategy to climate change. The number of actors involved varies along the chain, creating a bottleneck on the retailing stage (Fig. 2c). For instance, a total of 600 thousand farms hosts approximately 23 million dairy cows unevenly spread out across the EU but concentrated within the already mentioned dairy belt. The organization of the dairy sector is mainly predominated by cooperatives, where farmers and the industry work together to produce raw milk and process it into dairy products. Other types of structures exist such as individual producers (where farmers sell the raw milk directly to the industry) or individual intermediary groups (where the raw product is sold to the industry through an intermediary) (Augere-Granier, 2018). After the raw milk is manufactured into different dairy products for human consumption, they are distributed to hypermarkets and supermarkets, which both dominate 64% of the market share. The remaining 16% belongs to independent markets and the rest 20% to grocery stores (Merdji, Tozanli, & Kussman, 2015). Dairy products are mainly purchased by approximately 450 million consumers of dairy products in the EU (Eurostat, 2021).

2.2. Mind-map creation and keywords definition

Due to the lack of literature that assesses both sides of the interaction in the same study, two parallel separate searches were required to cover the whole interaction and aim the purpose of this study. Thus, first, relevant keywords for the interaction were defined and placed into circles on a mind-map (Fig. 3). It helped to have a visual representation of both sides of the interaction (blue and yellow colours) and understand how they were connected (thick black line). Eventually, combinations with the defined keywords were done to obtain relevant studies that cover the interest of the present review paper. A first set of keywords to bring literature that analyses the biophysical impacts of climate change on the dairy products value chains were defined as: "Climate change" + effects + (impacts OR "biophysical impacts") + ("food safety" OR waste) + ("Dairy sector" OR "dairy value chain" OR "dairy products"). The second set of keywords to obtain studies that evaluate the contribution of the dairy sector to climate change and other environmental impacts were also defined as: ("Dairy sector" OR "dairy value chain" OR "Dairy products") + ("GHG emissions" OR "global warming") + "Land use change" + (water OR eutrophication) + (LCA OR "Life Cycle Assessment").

2.3. Definition of selection filter and final selection of relevant references

Search engines such as Scopus and Google Scholar were used and, at this point, the two searches were very broad and an unmanageable number of papers were captured. To narrow it down the following selection filter was applied and only peer-reviewed studies, review papers, and international scientific reports in English, ranging the past 10 years (i.e. 2010-2020) and located in Europe, were kept.

In addition, specific criteria were included depending on the side of the interaction to obtain relevant literature:

- For the literature search on the contribution to climate change by the dairy sector, the following criteria were applied: i) studies with a life-cycle perspective at least with a cradle-to-farm-gate approach, ii) studies on dairy products or comparisons versus plant-based products; iii) studies considering GHG emissions in complementation with the evaluation of land use change and/or water use and eutrophication, iv) prospective LCA studies with a near term vision (2050). In addition, studies on the evaluation of the environmental performance of diets and studies on carbon sequestration as a mitigation strategy were out of the scope of this paper.
- For the literature search on the effects of climate change on the dairy sector, only studies that focused on evaluating the biophysical impacts were considered, leaving aside studies analysing the socio-economic impacts.

After applying the selection filters, a total of 44 studies were selected for in-depth revision (see Tables S1 and S2 of the Supplementary Information). Their detailed analysis, both using a life cycle perspective, is presented next: whereas section 3 analyses 26 studies that evaluated the

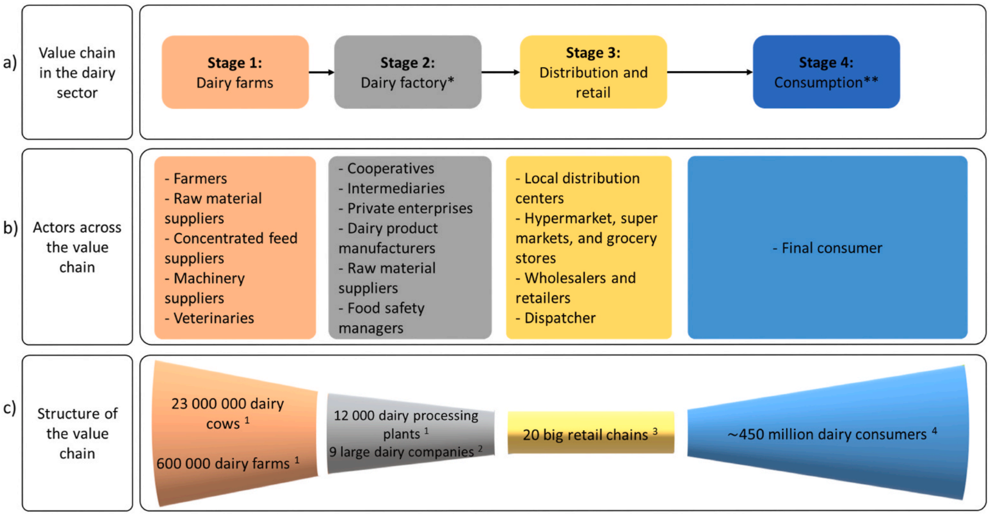

Fig. 2. A visual representation of the composition of the dairy sector. a) Typical lifecycle of the dairy products value chains, including their stages from farm to fork, b) actors involved in the dairy sector across the stages, and c) represents the structure of the dairy value chain. [1] Data from European Parliamentary Research Service (2018)//[2] Data from van Battum and Ledman (2019)//[3] Data from www.retail-index.com//[4] Eurostat (2020) * Milk collection at dairy farms is included at the dairy factory stage. ** Transportation of products from the retail is included at the consumption stage.

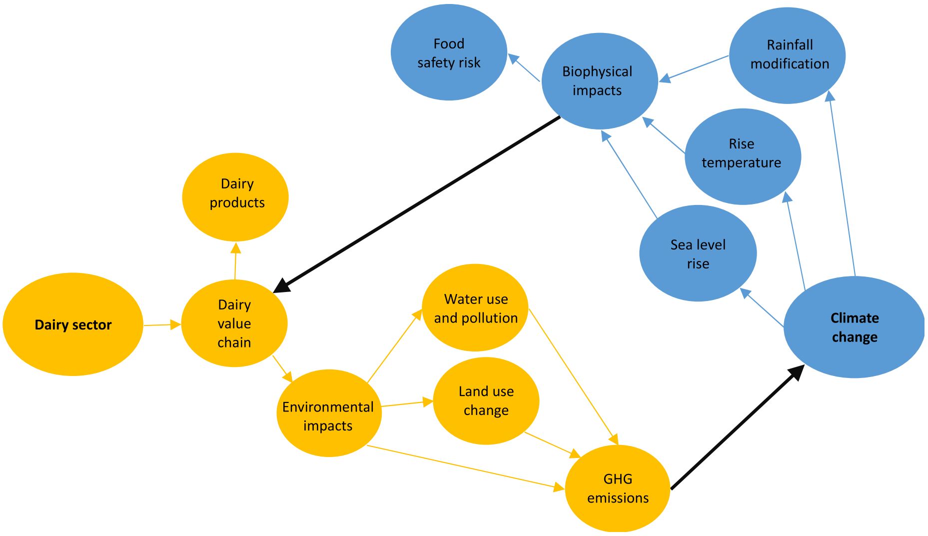

Fig. 3. Mind map of the dairy sector - climate change interaction. Black line represents the identified connections.

GHG emissions and other environmental impacts of the dairy sector, section 4 looks at the 18 studies focused on the climate change effects to extract possible elements of the dairy sector affected or benefited by this global issue.

3. Dairy SECTOR'S contribution to climate change

Based on the 26 studies obtained from the literature search, this section aims to analyse the main sources along the dairy value chain that contribute to climate change, even when the motivation behind the studies remains wide variable. For instance, the majority (19 out of 26) focused on raw milk and a particular dairy product and evaluated their contribution to global warming (Fig. 4). Among these 19 studies, authors that focused on raw milk at dairy farms stage, such as O'Brien et al. (2012), have also compared the raw milk production under different productive systems (i.e. pasture-based versus confined dairy systems). Henriksson, Flysjö, Cederberg, and Swensson (2011) have analysed the influence of different on-farm practices on GHG emissions of dairy farms. Zehetmeier et al. (2014) have evaluated the influence of uncertainties on GHG emissions methodological choices. Other authors analysed particular dairy products such as processed milk (Djekic, Petrovic, Božičković, Djordjevic, & Tomasevic, 2019; González-García, Castanheira, Dias, & Arroja, 2013; Roibás et al., 2016), yoghurt (Belo et al., 2015; Djekic et al., 2019; González-García, Castanheira, & Arroja, 2013; Vasilaki, Katsou, Ponsá, & Colón, 2016), cheese (Dalla Riva et al., 2017; van Middelaar, Berentsen, Dolman, & de Boer, 2011) and butter (Flysjö, 2011a; Nilsson et al., 2010).

Among the remaining studies, 3 papers reviewed the environmental performance of various types of dairy products (Djekic et al., 2014; Yan et al., 2011; Üçtuğ, 2019), all concluding that dairy farm stage is the largest contributor to the total different environmental impacts analysed; Scholz, Eriksson, and Strid (2015) analysed the contribution to climate change by the waste of perishable dairy products at the retail stage; and finally, 2 studies zoomed out the scope and covered a diet perspective considering the whole life cycle, whereas Muñoz, Milà i Canals, & Fernández-Alba (2010) analysed the average diet of a country, González-García, Esteve-Llorens, Moreira, and Feijoo (2018) compared diets rich in animal products (including dairy and meat products, which are two closely connected systems) versus vegetarian-based diets.

Along the dairy value chain, different sources of GHG emissions have been identified (Fig. 5). Regardless of the individual motivation, all studies identified dairy farms as the largest contributor to global warming, accounting for roughly 80% of the total CF of dairy products. At this stage, the main sources of GHG emissions are attributed to the CH_4 emissions from enteric fermentation and, to a lesser extent, to N_2O emissions from fertilizers for the on-farm feed production (i.e. roughage) and off-farm feed production (i.e. concentrated feed), to N_2O and CH_4 emissions from manure management, and to CO_2 emissions from the use of inputs at the farm such as energy and water use (FAO & GDP, 2018). The rest of the stages are responsible for the remaining 20% and also need to be analysed. In the second stage, the raw milk is collected from dairy farms and transported to the dairy factory. The CF of this stage is attributed to raw milk collection, management of waste and other inputs such as energy consumption, products during cleaning activities and packaging (Roibás et al., 2016). In the next third stage, the manufactured dairy products are distributed for their retailing and then purchased by consumers at the fourth stage. The GHG emissions of these two last stages are mainly related to product waste, use of refrigeration of perishable dairy products and transportation (Yan et al., 2011). Whereas product losses occur at dairy farms and dairy factories, product waste is related to retail and consumer stages (FAO, 2011).

A more detailed analysis of elements contributors to GHG emissions from a life cycle perspective is given in the following subsections. The elements are sort based on their share of the total CF contribution of dairy products. Additional comments on the other indicators related to water and land use are also provided.

3.1. Dairy farms

3.1.1. Enteric fermentation

Direct CH_4 emissions from cow enteric fermentation is the main contributor to the CF at dairy farms, with relative contributions varying from 35 to 59% of the total GHG emissions from this stage (FAO & GDP, 2018; Flysjö, Henriksson, Cederberg, Ledgard, & Englund, 2011; Morais, Teixeira, Rodrigues, & Domingos, 2018; Roibás et al., 2016).

The amount of CH_4 produced from enteric fermentation is mainly linked to the dry matter intake (DMI) of cows, which is also linked to the milk yield. Roibás et al. (2016) have analysed the influence of providing high-quality dry matter to cows, showing positive reductions of the CH_4 emissions of enteric fermentation.

Enteric methane emissions are rarely measured, instead, they are estimated from the emission factors (EFs) proposed by the IPCC guidelines (IPCC, 2006). A tier represents a level of methodological complexity and usually, three tiers are provided: a Tier 1 method is a simplified approach that considers a default emission factor (EF) to estimate the annual CH_4 emissions from enteric fermentation per dairy cow; a Tier 2 method is a more complex one that includes gross energy intake and specific methane conversion factors; lastly, a Tier 3 method is

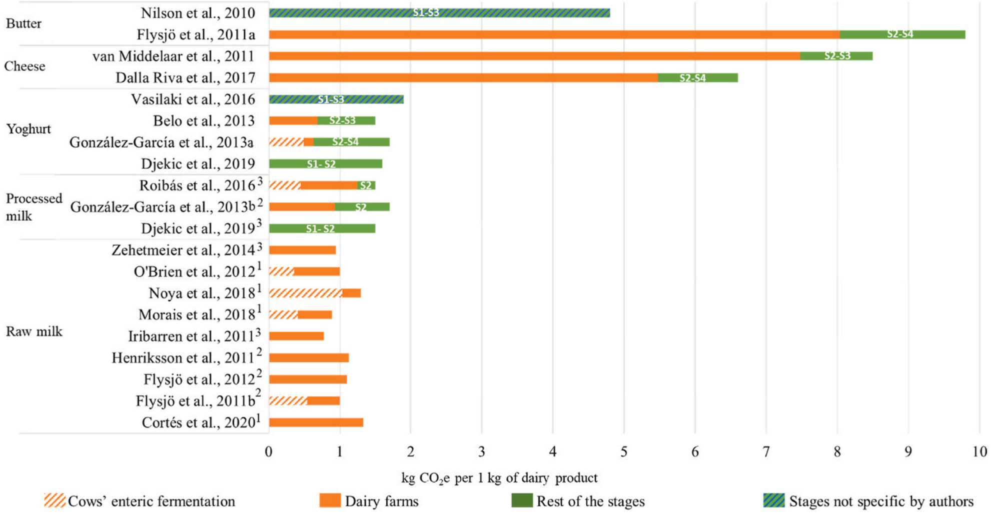

Fig. 4. Carbon footprints per 1 kg of dairy product reported from the literature review. Orange colour corresponds to the relative contribution to the total CF from the dairy farm stage. For those studies in which the contribution of enteric fermentation was mentioned, orange and white stripes represent the enteric fermentation. Green colour corresponds to the rest of the stages in those studies with broader system boundaries, analysing beyond the dairy farm stage. Lastly, studies that do not provide the relative contribution per stages are represented in blue and green stripes. These studies do not provide the relative contribution per stages and they only mentioned the total life-cycle CF per dairy product. ^{1} 1 kg of Fat and Protein Corrected Milk (FPCM). ^{2} 1 kg of Energy Corrected Milk (ECM). ^{3} Different functional units: 1 kg of raw milk, 1 kg of milk and 1 kg of packaged UHT milk, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

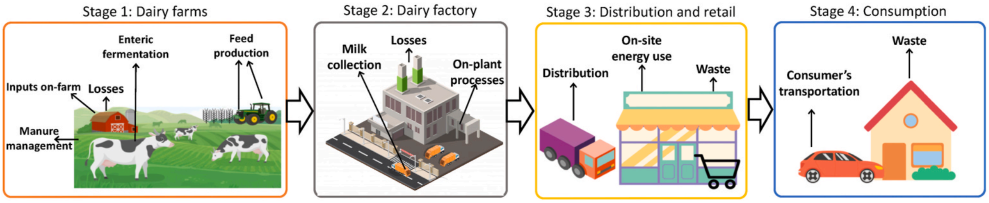

Fig. 5. Overview of the main sources of GHG emissions along the four stages of the dairy value chains, which are further described in section 3.

a country-specific method that provides a more complete level of detail, in which cow's diet, cow's breed, metabolic efficiency and productivity data are included (IPCC, 2006; Morais et al., 2018). Among the reviewed literature, the EFs reported by the IPCC (2006), i.e. tier 1 and 2, were the most commonly used approach (see for example Cortés, Feijoo, Fernández, & Moreira, 2020; Morais et al., 2018; Noya et al., 2018). Other authors such as Roibás et al. (2016) and Flysjö et al. (2011b) chose country-specific methods (i.e. tier 3) to quantify the CH_4 from enteric fermentation as their specific objectives required to do so. For instance, through a case study, Roibás et al. (2016) looked at a potential change of the CF of two types of milk based on the diet of the dairy cows. Flysjö et al. (2011b) pointed out the influence of different parameters on the CF of milk, among the selected parameters, they compared different methods to quantify the CH_4 from enteric fermentation.

3.1.2. *Feed production*

Feed production, which includes both off-farm feed production (i.e. concentrated feed) and on-farm feed production (i.e. roughage), is another relevant contributor to global warming at the dairy farm stage. Even without including manure management (see 3.1.3), feed production is responsible for approximately 25–30% of the farm's CF (FAO & GDP, 2018; Morais et al., 2018). This significant share is mainly associated with the direct N_2O emissions from the application of nitrogen (N) on the soil in the form of fertilizers and to the indirect N_2O emissions resulting from the NH_3 volatilized and the NO_3 leached. Another important source of GHG emissions, in this case as CO_2 emissions, is the production and use of fuel by agricultural machinery (including trailers, straw balers, harvesters and planters) (Djekic et al., 2014; Üçtuğ, 2019) and cereals production and their transport into the fodder factory (Gerber et al., 2010). Lastly, another contributor to the CF related to feed production is the emissions from land use change (LUC). LUC occurs off-farm when natural areas are shifted into land for crop cultivation required in feed concentrated and roughage, impacting the natural carbon cycle. Including or excluding LUC emissions significantly influences the total CF of dairy products. For example, Flysjö, Cederberg, Henriksson, and Ledgard (2012) evaluated the GHG emissions of producing 1 kg of ECM from cradle-to-farm-gate in Swedish dairy farms. They reported 1.13 kg CO_2e per kg of ECM when excluding LUC and 1.23, 1.26, 1.60 and 2.91 kg CO_2e per kg of ECM when including LUC using four different methodologies from (Gerber et al., 2010; Leip et al., 2010; Audsley et al., 2019 and Schmidt, Reinhard, & Weidema, 2011).

Feed production also requires water, which varies depending on the region, type of crops grown and management of the cropland (i.e. rainfed or irrigated). Also, the use of fertilizers (i.e. manure and synthetic) causes eutrophication, since nitrogen and phosphorous leaches to the receiving water bodies, as well as aquatic ecotoxicity. The percentage of applied N leached to water depends on the climatic conditions, reaching 30% in regions in which the precipitation is higher than evaporation (IPCC, 2006). Regarding P, the leaching factor reaches 3% (Roibás et al., 2016). Water eutrophication associated with cow's feed production has been addressed using two different approaches. On the one hand, González-García, Castanheira, Dias, and Arroja (2013) addressed it under the eutrophication potential (EP) category and concluded that the application of fertilizers contributes to nearly 57% of the total EP of dairy farms. On the other hand, Roibás et al. (2016) addressed the N and P associated to feed production under the grey WF concept from the WFN. It refers to the volume of freshwater required to assimilate pollutants and meet specific water quality standards. Then, the green WF is the rainwater that does not becomes run-off since it is stored or incorporated by plants and the blue WF refers to the freshwater extracted from water bodies and then consumed (Mekonnen & Hoekstra, 2011). On-farm and off-farm feed production contributed roughly 40%

to the total grey WF at the dairy farm stage and the rest associated with the green WF. Finally, Noya et al. (2018) included the contribution of N and P of feed needed in 1 kg of FPCM by using both approaches. They found that feed production contributed 65% of the total EP calculated at dairy farms mainly due to the use of fertilizers. Under a WF approach, the same activity contributed nearly 5% to the total grey WF at the dairy farm and the rest was associated with blue WF (7%) and green WF (88%).

3.1.3. Manure management

Manure management, which includes collection,[5] handling and storage of manure, is another contributor to the GHG emissions, making up roughly 9–15% of the dairy farm's carbon footprint (FAO & GDP, 2018; Noya et al., 2018; Roibás et al., 2016). Its related GHG emissions depend on the production and collection system, the composition of the slurry and climate conditions (Yan et al., 2011; Üçtuğ, 2019); so, amongst farms, these variables need to be considered since they might represent significant differences when calculating the CF of dairy products (Henriksson et al., 2011).

Manure management is a significant source of direct and indirect N_2O emissions. These emissions depend on the N contained in the animal excreta, and this, in turn, is related to the dry matter intake and the capability of the animal to retain the N in the body. Besides, manure management also releases CH_4, which depends on the type of handling and storage as well as the climatic conditions. To estimate both emissions, most of the authors have used the default emission factors (EFs) proposed by the IPCC guidelines (IPCC, 2006). However, some studies also have included country specific EFs, such as those calculated by O'Brien et al. (2012) where they used the mass flow model of Webb and Misselbrook (2004) for the United Kingdom to estimate the NH_3 emissions from excreta, to differentiate when cows were either in the confined or grazing season.

Even though excreta deposited in grazing systems is not considered as manure management, other authors such as Flysjö et al. (2011b) have identified and used country specific EFs to quantify N_2O emissions from these systems in New Zealand de Klein, Sherlock, Cameron, & van der Weerden, 2001 and Sweden Kelliher, de Klein, Li, & Sherlock, 2005.

3.1.4. On-farm inputs: energy and water use

Dairy farms use energy for milking, milk storage, lighting and cow cooling systems, which contribute to the raw milk CF. Even when on-farm energy use and their related contribution to global warming strongly depend on the specific production system implemented as well as the electricity mix of a certain region, its contribution to the total dairy farm CFs remains lower (i.e. lower than 6% according to O'Brien et al. (2012) than the other on-farm activities described previously).

Dairy farms also use freshwater mainly to provide drinking water to animals and to carry out on-farm cleaning activities (e.g. barn, milking equipment and milk storage tank) (Djekic et al., 2014). However, these cleaning activities represent aquatic toxicity due to the utilized cleaning agents (González-García, Castanheira, & Arroja, 2013).

3.2. Dairy factory

The literature review done revealed that GHG emissions at the dairy factory are associated with raw milk collection, on-site processes, packaging material provision, milk losses and wastewater treatment.

Raw milk is collected and transported to the dairy factory while keeping product safety objectives. GHG emissions are linked to milk collection due to the refrigerated conveyance and the use of refrigerants to maintain cold storage (Djekic et al., 2014). Authors who covered milk collection reported a low contribution to the total CF of dairy products: < 2% being reported together with final product distribution (see section 3.3) according to Flyjsö (2011a) and Roibás et al. (2016).

Once the raw milk enters the dairy factory, on-site processes such as thermal treatment, separation, pasteurization, cooling, incubation and cooled storage require energy contributing to GHG emissions (Dalla Riva et al., 2017; González-García, Castanheira, & Arroja, 2013). Products manufactured and technical characteristics of the dairy plant are factors that influence the on-site energy use (Djekic et al., 2014; Gerber et al., 2010). Cleaning-in-place operations also contribute to GHG emissions, due to the energy and water use as well as the cleaning agents production that are involved (Vasilaki et al., 2016). Wastewater streams produced and other cleaning activities at the factory impact the environment. Before being discharged, those streams must be treated to meet the legal requirements and that means energy and chemicals use. Wastewater treatment together with waste management accounted for 1.5% of the total CF of producing 1 kg of high-moisture cheese (Dalla Riva et al., 2017).

The final products are packaged, where the material used and the final presentations available for consumers varied a lot depending on the dairy product (milk, yogurt, cheese) as well as within the product itself (pasteurized versus UHT milk). For instance, the manufacturing of packaging materials contributed to 7% of the total CF of 1 L of packaged UHT milk (Roibás et al., 2016). Efforts have been made in past years to reduce the environmental impact of packaging materials. The introduction of bio-based materials has resulted as a promising option to reduce its CF throughout the flexibility of dairy product manufacturers to choose packaging materials that guaranteed less environmental impact.

3.3. Distribution and retail

Manufactured dairy products are distributed to regional distribution centres and from there to the different selling points. The energy use during the transportation activities depends on several factors: distances travelled, type of fuel used (i.e. conventional or renewable), and mode of transportation (Djekic et al., 2014), which is not only restricted to terrestrial but also maritime. Once at the retailers, the main contributors to GHG emissions are linked to on-site air conditioning systems, lighting and refrigerated cabinets to ensure the safety of perishable dairy products.[6] The total energy consumption of a large number of supermarkets (322 000) was studied and it was found that on average 35–50% corresponded to the refrigeration while the rest was attributed to other activities on-site, i.e. air conditioning systems and lighting (James & James, 2010).

Food waste at retailers, due to products not purchased before their sell-by date, has been identified as a significant contributor to the CF of food (FAO, 2011). As mentioned above, one of the selected papers focused on this evaluated the contribution to climate change of food waste in six supermarket retail stores. They reported average yearly waste of 90 tonnes of food leading to 140 tonnes of CO_2e per supermarket and where the dairy products department contributed roughly 6% to that total figure (Scholz et al., 2015).

3.4. Consumer

At the consumer stage, GHG emissions are mainly attributed to the dairy products transportation to households, in which different choices related to the consumer's activities need to be considered such as shopping frequency and transportation mode (Flysjö, 2011a). In other cases, dairy products are consumed in other places (e.g. restaurants, coffee shops …), and thus, the transportation to these sites corresponds

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[5] Note that in grazing systems, excreta deposited directly on fields is not included within manure management.

[6] Note that some dairy products, such as UHT milk and derived products, have long shelf life (up to 6–9 months) at ambient temperatures and do not required refrigeration.

to the distribution stage. Also, GHG emissions are associated with the electricity consumed to refrigerate dairy products that require cold storage (González-García, Castanheira, & Arroja, 2013), in which the respective PCR of processed milk (PCR, 2013, p. 17) provides guidance to quantify it, and for heating liquid milk in some cases. Other environmental impacts are more related to waste and wastewater streams, such as those related to dairy product waste, packaging management, human digestion and resulting wastewater treatment.

Regarding product waste, some dairy products are often not consumed within the recommended time, and therefore, waste occurs at the consumption stage. According to FAO (2011) the average waste of dairy products reaches roughly 7% at this stage. Even though the product waste happens at this stage, large amounts of natural resources and GHG emissions occur along previous life cycle stages in the production of dairy products. Waste at this stage, means that all these inputs and outputs were generated in vain. Thus, product waste prevention at the consumer stage has a significant impact on earlier stages of the dairy value chains.

Concerning waste management of packaging at households, studies that evaluated it concluded that GHG emissions from waste management depend on the specific treatment. Amongst the waste treatments identified were waste incineration plants (Flysjö, 2011a), recycling, sanitary landfills and less frequently energetic valorisation and composting (González-García, Castanheira, & Arroja, 2013), however, its individual contribution to the total CF was not available.

With respect to human digestion, this stage has been excluded in all the paper revised even when it might have a significant contribution to the total CF of food products as reported by Muñoz, MilàI Canals, and Fernández-Alba (2010) when analysing the entire life cycle of food products in a context of the Spanish average diet using their model Muñoz, Milà i Canals, & Clift, 2008 and reporting that human digestion together with wastewater treatment contributed 3% to the total CF. This value was shown close to the one obtained by Schmidt and de Saxcé (2016), in which they evaluated the CF of the total product portfolio of a dairy company (i.e. Arla Foods) and determined that human excretion contributed 1.5% to the total CF.

Lastly, Djekic et al. (2019) analysed the GHG emissions linked to the average weekly intake of milk and yoghurt in Serbia. By using the LCA methodology together with a consumption survey, they estimated a mean of 2.24–2.26 kg CO_2e per person per week at the consumption of both products.

Beyond the activities related to the consumption stage described previously, consumer's dietary patterns and additional factors as shown in Fig. 1 also influence the GHG emissions and other environmental impacts. Nevertheless, an evaluation of the environmental impact of diets is beyond the scope of the present study, and thus, keywords on diets were not part of the selection filter. Although the study from González-García et al. (2018) has a diet focus, it was included as the authors emphasize dairy products. They analysed a total of 66 current dietary scenarios and identified diets with the presence of dairy products as the diets with the highest GHG emissions. The values estimated ranged from 3.6 to 6.3 kg CO_2e per person per day from cradle-to-consumer.

4. Biophysical impacts of climate change on the dairy sector

Based on the 19 papers identified in section 2, the following chapter aims to describe the biophysical impacts of climate change on the dairy sector. Among the different climate change effects identified, temperature modification, rainfall variation, sea level rise, and combinations thereof have been pointed out as the most significant effects that will represent biophysical impacts on the dairy value chains in Europe. The identified effects match those defined by EFSA (2020).

Since the effects of climate change will vary over Europe depending on the geographical region, the dairy sector will not be hit uniformly by climate change. According to their vulnerability to the climate change effects, a total of six biogeographical regions were identified across Europe (European Environment Agency, 2017): i) Atlantic (north-western Europe), ii) mountain regions, iii) coastal zones, iv) boreal (northern Europe), v) continental (central and eastern Europe) and vi) Mediterranean (southern Europe). Most of the selected papers followed these six biogeographical regions and their expected trends, as will this paper.

In the past decades, significant research has been done to model the biophysical impacts of climate change and emerging risks on the agricultural sector, including the dairy sector (IPCC, 2014b). Authors have determined the climate change impacts and evaluated their severity on the dairy sector under two dominant approaches: i) the bottom-up approach focuses on local impacts and they are defined based on the past experiences of the actors involved in the product value chains (e.g. farmers); and ii) the top-down approach focuses on global and regional impacts and they are determined by using either global or downscaled climate scenarios into impact models and agronomic indices (IPCC, 2014). The IPCC (2014) states that the implementation of both approaches is a promising option to provide efficient decision-making and develop effective adaptation measures. The following sections describe the expected biophysical impacts of climate change on the dairy sector under both approaches.

4.1. Heat stress

Like any other animal in agriculture, dairy cows have difficulties coping with high temperatures and they are susceptible to experiment heat stress (EFSA, 2020) leading to the milk yield reduction, mortality increase and fertility rate decrease. Increment in temperatures because of climate change is expected to accentuate heat stress (European Environment Agency, 2019; Hempel et al., 2019). Vulnerable regions such as the Mediterranean are expected to experience the strongest warming mainly in summer (Hempel et al., 2019). The temperature rise will affect differently the dairy cows in confined systems than grazing systems.

The most widespread indicator to evaluate the effects of climate variables on ruminants is the Temperature Humidity Index (THI), which uses temperature and relative humidity as variables (National Research Council, 1971). Heat stress of a Holstein cow with an average yield (i.e. up to 35 kg/day) begins at THI = 68, which corresponds approximately to ±25 °C and ±15% relative humidity (Hempel et al., 2019). The impacts of heat stress in milk yield of dairy cows by 2050 were studied by Hempel et al. (2019), concluding that the number of heat stress events, (i.e. defined as the number of hours when the cow experiences at least moderate heat stress (THI $\geq$72)), in Mediterranean regions will be higher in comparison to central Europe: up to 500 additional heat stress events projected under a pessimistic scenario (RCP 8.5) versus up to 50. Moreover, they concluded that, while heat stress risk is projected in summer months in both regions, in Mediterranean regions heat stress events will also be expected in spring and autumn. Fodor et al. (2018) also projected to the mid-21st century the influence of heat stress on milk yield on dairy cows in the United Kingdom (i.e. Atlantic region or north-western Europe according to the European Environment Agency classification). Both studies projected a decline in the cow's milk yield when THI = 68: an average decrement of up to 2.8% relative to the current milk yield in Europe (according to Hempel et al., 2019) and a decrement of 2.4% in the Atlantic region (according to Fodor et al., 2018).

Besides impacting milk yield, several authors mentioned that the rise of temperatures might also influence milk quality (Misiou & Koutsoumanis, 2021; Hempel et al., 2019) and somatic cell count (Feliciano, Boué, & Membré, 2020), however, to the best of the knowledge of this review, detailed studies on this are not available yet.

4.2. Crop cultivation variability

Crop systems are closely connected to the dairy sector since they provide feed to dairy cows. Changes in temperature and rainfall are climate change effects projected to impact yield, growing seasons and quality of crops (EFSA, 2020). Considering the six biogeographical regions, the biophysical impacts of climate change on crops are not expected to occur evenly over regions and might represent an opportunity in some areas.

Northern Europe was identified as one of the regions in which crop yield will be positively impacted by the climate change effects. On the contrary, negative impacts are expected to occur in southern Europe. For example, wheat yields by 2030 were projected under two climate models, whereas in Northern Europe an increment of 20% was found, in Southern Europe, a decrement between −5 and −20% was detected (European Environment Agency, 2017). In the report of the European Environment Agency (2019), the authors also projected the changes of rainfed maize yields by 2050 using 11 climate models and found the same outcome: maize yield in Southern European regions is expected to decline to even 50% less in comparison with the yields reported in 2010, while yields in Northern Europe are expected to increase in 5% compared to the 2010 baseline. The same trend of reduction of maize yield in southern regions and an increment in northern regions were projected by Hristov et al. (2020).

Climate change will be also affecting growing seasons, meaning a delay or advancement of harvest dates in crops. This modification on the growing seasons of crops will be positive in some areas but negative in others. In fact, the enlargement of the growing season in northern Europe is expected to represent an opportunity as new crops could be introduced due to favourable climatic conditions in combination with positive water availability in this region as well (European Environment Agency, 2017). As an example, Battilani et al. (2016) has projected a geographical distribution of maize cultivation northwards, reaching latitudes up to 60° north in a near future. Differently, due to projected droughts and heatwaves in the summer season, crop cultivation of some crops might not be possible in this season and shift to the winter season, modifying the harvesting in Mediterranean regions (European Environment Agency, 2017).

Lastly, another climate change effect identified that somehow might impact the dairy sector, including crop cultivation, is sea level rise. This effect might provoke submersion of coastal agricultural land and deltas due to saltwater inundation, causing a displacement of agriculture towards other areas (Falloon & Betts, 2010; IPCC, 2014). Moreover, sea level rise is expected to cause seawater intrusion into freshwater reservoirs, affecting the health of essential crops for dairy cow's feed (EFSA, 2020), coastal agriculture as well as freshwater availability for agricultural coastal regions (European Environment Agency, 2019).

4.3. On-farm water availability

Water availability is critical for dairy farms, both for agriculture activities but also for other activities such as facilities cleaning and cow drinking. Concerning the latter, even though cows' water intake is smaller than the water required for feed production, supplying this natural resource in quantity and quality is vital for the animal to handle warm environments and relieve heat stress (Gauly et al., 2013). However, expected modifications in the rainfall patterns and increases in temperature will affect the water cycle, leading to water shortages or water scarcity (Rojas-Downing et al., 2017). A change of these climate variables will increase the evapotranspiration rates, and thereby, the crop water requirements are expected to increase (European Environment Agency, 2019). In Europe, the severity and frequency of droughts are projected to occur across Europe but mainly in southern and south-eastern European regions (European Environment Agency, 2017). In addition, there is also evidence of changes in the groundwater recharges, which vary across Europe. Whereas in northern and north eastern areas the annual recharges are projected to increase (+50%), in southern Europe the groundwater annual recharge is expected to decrease (−25%) by the end of the century in comparison to 2010. In this context, farms located in semi-arid environments, which rely on pumping groundwater, might see an increase in their pumping cost to extract groundwater required in the on-farm activities (Ciscar, Feyen, Ibarreta, & Soria, 2018). In addition, rising temperatures affect the water cycle, and thus, freshwater supply.

4.4. Cow diseases and crop pests' pressure

The rise of average global temperature is expected to increase the reproduction and distribution rate of certain pathogens, having negative impacts on both dairy cows and crops' health (EFSA, 2020). Regarding emerging risks on cows, gastrointestinal nematodes and viruses are the major threats causing considerable animal losses in herds (Gauly et al., 2013). A recent report of EFSA (2020) identified 34 main issues related to animal health due to climate change in the near future, being the biting midges of *Culicoides imicola* (vector of bluetongue, which is a viral disease transmitted amongst ruminants) scored with the highest risk in terms of impact and likelihood of emergence in the near future. Samy and Peterson (2016) estimated the global distribution of the bluetongue virus in Europe under climate change conditions by using global climate models and four RCPs, and projected that the likely rise of temperature in 5 °C related to the high-emissions scenario (RCP 8.5) will create suitable conditions for the bluetongue virus in the north of Europe by 2050 so this virus will spread to regions where it was not present before, causing outbreaks leading to high cow's mortality rates.

Besides risks on cows, the combination of climate change effects, rise of temperature and rainfall modification, will represent emerging risks on crop pests such as mycotoxins (Chhaya & Cummis, 2021). Crop pests will aggravate the farmer's concern of providing quality and safe feed to animals and an additional use of pesticides could be expected as an attempt to cope with pests pressure on crops (EFSA, 2020). Battilani et al. (2016) developed a model to predict the aflatoxin B1 contamination in maize and wheat crops in Europe under the climate change effects for two scenarios: an optimistic (temperature rise of 2 °C) and a pessimistic (temperature rise of 5 °C), covering to 2050. In both cases, they identified that aflatoxin contamination of maize will expand its geographic limits northwards from the current 45°N to 60°N. The Mediterranean and Eastern Europe were the regions presenting higher risk, meaning a rise of animal exposure to aflatoxin B1 due to contaminated feed, and therefore, affecting animal health and raw milk safety.

4.5. Product safety risk: food losses and waste

In the food industry, product safety is crucial to prevent contamination and avoid any harm to consumers as well as product losses. As a result of climate change, higher temperatures and changes in rainfall are associated with the presence of food-related hazards (i.e. biological and chemical hazards), affecting the safety of dairy products (van der Spiegel, van der Fels-Klerx, & Marvin, 2012) which is directly linked to potential food losses and waste along the value chains.

Food-related hazards are expected to impact the safety of raw milk and dairy products. The common identified biological hazards present in raw milk are mastitis causative pathogens. Mastitis is commonly caused by *Escherichia coli*, *Staphylococcus aureus, Streptococcus uberis*, and rarely by *Listeria* spp. (Feliciano et al., 2020). Climate change is expected to increase mastitis occurrence in lactating cows, meaning an increment of these biological hazards in raw milk (EFSA, 2020). The safety of raw milk is also indirectly affected by farmer's practices such as poor feed storage, on-farm hygienic conditions (i.e. milking equipment and barn) and animal husbandry. Microbial growth can alter the safety of raw milk during its transportation to the dairy factory, thus, food safety controls take place at the entrance of the factory to avoid microbial contamination. Pre-processing treatments (i.e. filtration and thermalization) are treatments usually used before starting the main processing treatments (i.e. separation and pasteurization) that help in the removal of some microorganisms presented in the raw milk. After separation of cream from skimmed milk, both are pasteurized to remove or reduce pathogens at acceptable levels. However, some microbial hazards, like the ones described by Misiou and Koutsoumanis (2021), can survive thermal treatments and contaminate dairy products. In addition, the safety of dairy products is expected to be compromised by the presence of on-farm food-related hazards such as mycotoxins, which directly impact dairy products through contamination of cow's feedstuff, and which might be even more important under climate change conditions (Chhaya & Cummis, 2021).

The presence of the food-related hazards on the dairy products value chains is linked to losses and waste (FAO, 2011). Under current production and consumption trends, the global daily food waste generated per capita is projected to increase by 19% in high-income countries by 2050 in comparison to 2018 (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). In this context, dairy products will have a significant contribution in this expected increment of waste since they are one of the value chains with highest rates of product waste (FAO, 2011). Precise figures are difficult to obtained as a large number of changing factors out of the dairy sector-climate change interaction (e.g. consumption patterns, population growth and climate change governance) leads to large uncertainties so projections should be taken with care.

5. Dairy sector and climate change interaction

Once the key life cycle environmental impacts of the dairy sector as well as the main biophysical impacts of climate change on the sector have been identified and discussed separately, this section aims at describing their interconnections. So, Fig. 6 relates the effects of climate change and their biophysical impacts on the dairy sector with potential measures to confront those impacts and, finally, with the expected environmental consequences of implementing those measures all along the life cycle stages. Some of the identified environmental consequences are actually contributions to climate change, creating an aggravating nexus.

As already discussed, the temperature rise was found as the most substantial effect of climate change that affects the dairy value chains. Herds in dairy farms located in susceptible regions will experience a significant rise in heat stress, compromising the milk yield of lactating cows as well as the mortality rate of the animals. To deal with cows' heat stress, farmers need to define suitable measures based on the dairy production system implemented. For instance, in grazing systems, the most promising measure to reduce heat stress is the provision of shaded areas (European Environment Agency, 2017), while in confined systems, the use of cooling systems and/or water sprinklers to reduce heat stress risk seems to be the best solutions (Hempel et al., 2019). These measures entail the use of energy and/or water so they can lead to a variation of the related GHG emissions and water use. When evaluating the environmental consequences of higher energy use (as expected in this and other measures further discussed below), external factors such as the energy production profile need to be considered as an increment of the share of renewable energy sources in national electricity mix (IRENA, 2020). An increase in electricity use might not entail an increment in GHG emissions. Concerning water use, the capacity of water storage will become essential in regions where water shortages are expected to ensure water supply during dry and warm seasons when cows have more risk of experience heat stress. Besides those operational strategies, the genetic selection of dairy cows' more resistance against heat stress has been identified as a promising strategy to adapt to the extreme temperatures caused by climate change (European Environment Agency, 2017; Misiou & Koutsoumanis, 2021). In the dairy farms across Europe, the gene of slick hair has been used in the Holstein Friesian dairy cows to increase heat stress tolerance (Rovelli et al., 2020). Normally, the milk yield of dairy cows without this gene tends to decrease during the summer season but the milk yield of cows with this gene is not affected during this season and remained constant (Dikmen et al., 2014; Hansen, 2020). From an environmental impact point of view, a dairy herd more resistant to heat stress can result in less time of use of the on-farm cooling systems, influencing the CF. There have been efforts to continuously improve the cows' milk production by increasing their peak milk yield and reaching an earlier lactation through feeding strategies and genetic improvement (Bórawski, Pawlewicz, Parzonko, Harper, & Holden, 2020). However, all these improvements are likely to be outweighed in regions with a higher risk of heat stress.

Temperature rise together with heavy rainfall events is expected to benefit the geographic expansion of pathogens and increase as a consequence, cow's and crop's diseases. Farmers are likely to encounter the presence of newly introduced or expanded pathogens in their region and be pushed to take new measures to reduce outbreaks. The use of antimicrobials is one of the first measures to soothe cow's diseases, however, its excessive or inadequate use can increase the possibility of antimicrobial resistance (Misiou & Koutsoumanis, 2021). Apart from the

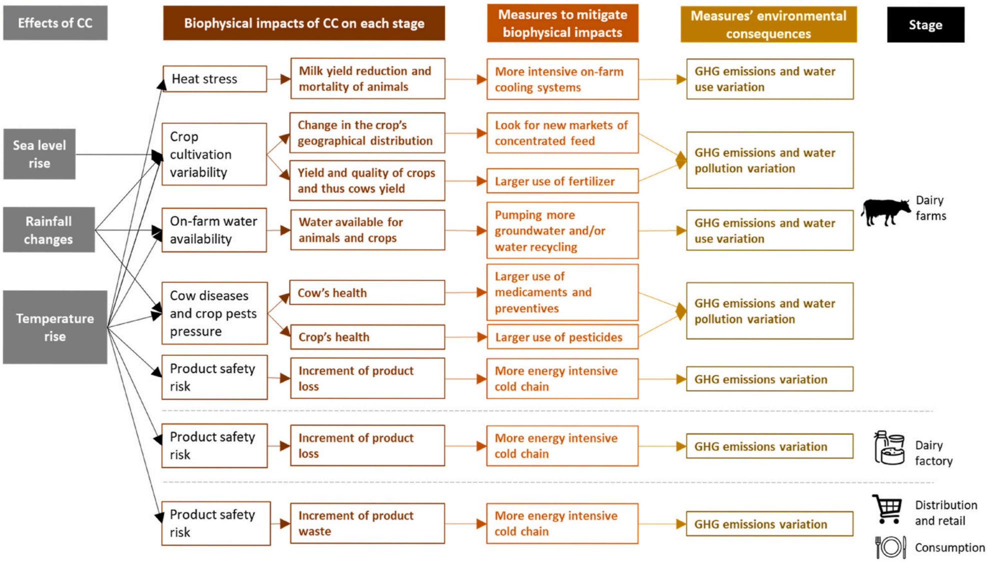

Fig. 6. Main interactions of the biophysical impacts of climate change (CC) on the environmental performance of the dairy value chains.

risk of increased antibiotic resistance, the use of antimicrobials entails an environmental impact. It is not only caused by the production of the drugs themselves but also related to the animal excretion and mostly, to the milk losses, which represent the major impact in both environmental and economic terms. Milk losses occur both directly and indirectly. The former is related to the actual milk that is produced but cannot be collected to be transported to the dairy as it does not meet the quality standards for human consumption due to the presence of residual drugs, while the latter is related to the milk that is not produced as cows' milk yield is reduced during the illness period (Hospido & Sonesson, 2005). Additionally, a combination of effects of climate change such as modification of temperature, rainfall and humidity levels are expected to benefit fungal growth during feedstuff storage, leading to its spoilage (Misiou & Koutsoumanis, 2021). Control the conditions in which feedstuff is stored and the use of preservatives are measures that are often used to reduce the chances of fungal growth. Also, since climate change is expected to affect crops' health, leading to a reduction of crop yield, the use of pesticides is a common strategy among farmers to fight against pests. However, the use of preservatives and pesticides to fight crops' pests has a negative impact on the environment, triggering eutrophication and global warming (Dalla Riva et al., 2017) as well as leading to death of essential pollinators (EFSA, 2020). Also, the production of the preservatives and pesticides creates unnecessary extra emissions to the air and water.

Yield, quality and the geographical distribution of crops will be influenced, either positively or negatively, by the combined action of climate change effects, affecting significantly the dairy farm performance. As a result of sea level rise, which has a low level of risk emergence, the projections show that salinization of coastal soils in Europe will affect the yield and quality of crops (IPCC, 2014). Regardless of the level of emergence, farmers in these regions need to make use of fertilizers and freshwater to confront soil salinization. Also, a combination of rainfall modification together with temperature changes can lead to a change in the geographical distribution of some crops, leading farmers to look for new suppliers of on-farm feedstuffs. Concerning the crops required in the concentrated feed, which are grown in off-farm areas (e.g. South and North America), the combination of these climate change effects will also affect their geographical distribution across these areas. In addition, cross-sectoral competition for available arable land is likely to increase, affecting the dairy sector and other forms of land use for food production (IPCC, 2014). At a micro-level, these effects of climate change will also represent an impact on the properties of the habitat (i.e. physical and chemical), modifying ecological interactions and leading to a competition for nutrients between species (i.e. crops versus invasive weeds) (European Environment Agency, 2017). The invasion of weed into croplands represents significant reductions during the cultivation of important on-farm crops (e.g. maize). More use of pesticides will be needed to fight invasive weeds and avoid these reductions (Peters, Breitsameter, & Gerowitt, 2014). In past years, scientific research has been carried out to improve crop yield, which is intended to continue improving in the coming years. However, likewise cows' yield improvement, the effects of climate change can represent a challenge, slowing down this continuous process of crop yield improvement. Thus, efforts are now directed to gain knowledge in how to create resilient crops that can persist in unfavourable conditions (i.e. under extreme weather events and nutrient deprivation) (Dhankher & Foyer, 2018). Despite the efforts done, there is clear evidence that more fertilizer and pesticide use to confront salinization and invasive weed, respectively, could lead to an increase of emissions to air and water as well as aquatic toxicity.

Passing to water available on-farm, a modification in the rainfall patterns can lead to water shortages. This climate change effect together with sea level in coastal regions can aggravate the situation, provoking seawater intrusion in coastal aquifers and wells (Colombani, Osti, Volta, & Mastrocicco, 2016). Pumping more groundwater and/or recycling water to supply animals and crops are measures identified (Ciscar et al., 2018). However, there is a so-called nexus between water and energy: energy is required to supply freshwater to animals and water is needed to produce the required energy Olsson, 2015. Thus, on-farm water supply also influences the on-farm electricity consumption, which, as mentioned in section 3, was identified as an important contributor to GHG emissions.

With regards the last identified biophysical impacts, product safety risk appears in all the life cycle stages as shown in Fig. 6. The emergence of product safety risk is expected to occur due to a higher incidence of food-related hazards as a response to climate change, leading to product losses and waste. Many initiatives and strategies have been launched to fight food losses and wastes since they do not only mean the disposal of the raw material or product itself but also the resources and emissions needed for its production. A reduction of both, losses and waste, can reduce the environmental impact of the dairy sector. In order to ensure product safety, the cold chain is maintained at all production stages from the raw milk collection, refrigeration at the dairy factory to the retail stage until the product reaches the consumption stage,. However, as climatic conditions change, microbial growth in dairy products will occur in poorly managed cold chains, and as a consequence, there will be an increment of raw milk lost and/or dairy products wasted (Fanzo, Davis, McLaren, & Choufani, 2018). At the dairy factory stage, more energy-intense thermal processing will be required to reduce the level of food-related hazards coming from dairy farms and keep the optimal levels of product safety (Malliaroudaki, Watson, Ferrari, Nchari, & Gomes, 2021). The dairy industry will keep as main priorities guaranteeing the consumer's health and avoiding product losses by taking the appropriate measures. Nevertheless, a growing and already existing tendency will be to assess any corrective measure in terms of their environmental consequences, and notably, of their contribution to climate change. To evaluate the future environmental performance of this sector in a climate change era, a prospective LCA is a promising framework that can be applied to capture all the possible changes previously described in this section, such as the on-farm practices (e.g. larger use of pesticides, fertilizers and/or veterinary drugs) and technology (e.g. electricity mix, cold chain, dairy factory processes) (Cucurachi, Van Der Giesen, & Guinée, 2018).

6. Conclusions

The dairy products demand will increase in the near term. However, the European dairy sector also needs to prepare for the unequal effects of climate change. This sector could be directed to a large number of possible paths in which opportunities and threats can be presented. Measures to mitigate these threats may represent environmental consequences that contribute, in turn, to climate change and other environmental impacts. This global issue will not only affect the environmental sustainability of this sector but also its product safety along the dairy value chains. To begin preparing this sector for the future effects of climate change, adaptation strategies to ensure product safety should also include environmental sustainability. Therefore, there is a need to develop a framework, where different tools are integrated, to aid the dairy sector to face these challenges and ensure food safety while improving its environmental sustainability in a climate change era. As a starting point in the development of such framework, this paper aimed first to define and analyse the interaction between the dairy sector and climate change to capture the connections in a matrix (Fig. 6). It provided an understanding of how the environmental sustainability of the dairy sector could be affected by the climate change effects. This review also allowed to look at the possible directions in which the dairy sector will go in the near term, aiding in the definition of future scenarios that will be part of the integrated framework. This review should be continued with quantitative evaluations of the defined matrix to estimate how much the environmental sustainability will change, either positively or negatively. The transformation of data on valuable information will support the preparation of the dairy sector for its adaptation to climate change in the near term. Despite a near future full of uncertainties, this paper has placed the first stone of the way to support more effective decision-making on the definition of environmentally sustainable adaptation strategies along the different stages that comprise the dairy sector and its main product value chains. The European dairy sector commits to fulfilling the Sustainable Development Goals (SDGs) since it is responsible for significant amounts of GHG emissions and other environmental impacts (European Dairy Association, 2017). This paper supports the dairy sector towards its delivery of the SDG 13 (Climate Action). Fig. 6 and its further quantification can build knowledge, so the actors in the dairy sector can identify the possible scenarios that this sector will face in a climate change era (SDG 13.3). Also, Fig. 6 can aid as the basis to design climate change adaptation strategies while reducing environmental impact, and as a result, it will promote and contribute to environmentally sustainable and resilient food production (SDG 2.4 and SDG 12). In addition, this study mentions the need of increasing water efficiency when the dairy sector faces water scarcity or shortages periods caused by climate change across vulnerable European regions (e.g. Mediterranean) (SDG 6.4). Lastly, climate change is expected to increase the proliferation of spoilage microorganisms. It will lead to raw milk losses and dairy products waste (Misiou & Koutsoumanis, 2021), meaning that the consumption of natural resources and the emissions of GHG will be in vain. Fig. 6 draws the pathway to connect from product safety, raw milk losses, dairy products waste to related GHG emissions. Thus, it allowed identifying the side effects of potential measures to reduce such losses and waste under climate change conditions (SDG 12.3). Moreover, the revision provided will also benefit other actors outside the dairy sector, such as policymakers, in the further definition of actions within the key European strategies, such as Farm-to-Fork, dealing with the required transition to a sustainable food system while adapting to the impacts of climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2021.09.001.

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