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Challenges When Assessing Water-Related Environmental Impacts of Livestock Farming: A Case Study of a Cow Milk Production System in Catalonia †

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Abstract: Water availability is a local issue of growing importance in Mediterranean areas where water scarcity linked to climate change and population growth is already leading to increased competition for this resource. This study is aimed at the following: (i) assessing the water-related environmental impacts (water use, freshwater ecotoxicity and eutrophication, marine eutrophication, acidification, human toxicity, and ionizing radiation) along the production chain of cow milk in Catalonia, northeastern Spain; and (ii) addressing the issues encountered (modelling choices, data gaps and inconsistencies) which t can affect the quality of results when performing a water-footprint comprehensive assessment, focusing on water use and associated water scarcity impacts. The scope included the process from the extraction of raw materials up to the distribution of the packaged fat- and protein-corrected milk to the distribution centres of the supermarket chains and markets. Results showed the farm stage to be determinant (contributing to over 60% of the impact), due to the impact of feed production. Impact results were in the range of the European benchmark given by the Product Environmental Footprint Category Rules for dairy products, except for the water scarcity footprint which was one order of magnitude larger than the reference value, due to water scarcity in Spain. Considering compound feed ingredients with a lower water scarcity footprint, and research into slurry treatment for its use as irrigation and cleaning water (without compromising safety and health) could help reduce this impact. Water accounting and traceability along the production chain could support the dairy industry to take responsibility for the consequences of their production choices.

Keywords: milk; livestock farming; LCA; sustainability; water use; water scarcity; water footprint

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1. Introduction

Despite close to three quarters of the Earth's surface being covered by water, less than 1% of this water is available freshwater, when excluding inaccessible water such as glaciers and ice caps, atmospheric and groundwater at inaccessible depths, or highly polluted water bodies [1]. Freshwater availability is crucial for the maintenance of life on our planet, and essential for food production. In fact, agriculture is one of the main freshwater users, using about 70% of the global freshwater resources [2], of which 40% are estimated to be blue and green water used for livestock feed production globally [3].

Moreover, the small fraction of available freshwater is unevenly distributed across the planet. For example, in the Mediterranean region of Europe, freshwater availability is a limiting factor for agriculture performance and livestock production [4,5]. In Catalonia (northeastern Spain), where the study area is located, the extreme drought of 2023 has exacerbated water scarcity and led to severe water restrictions on agricultural, industrial, and recreational use. Furthermore, water scarcity due to climate change and population growth will lead to even more increased competition for this resource in the near future [5]. Therefore, managing water appropriately in livestock systems is vital for a thriving environment and human life. For water management, it is crucial to know the amount of water used and how (if in situ or extracted from the water body), but also how much water is regionally and temporally available, and how pollutant emissions impact freshwater ecosystems. A life cycle (LC) perspective, assessing all water uses and pollution along the supply chain of the livestock production systems and products is essential as it allows for the identification of environmental impact hotspots. Efforts to reduce the impact can then be focused on improving the main impact contributors causing them, which helps to optimize impact reduction. Furthermore, an LC perspective helps to avoid the impact burden shifting over time and space. While water is a local issue [6], the impacts of mitigation measures need to be considered globally. Thus, considering the whole LC prevents taking measures to reduce the water footprint locally (at the farm level) while neglecting increased impacts from upstream- or downstream-production processes. Thus, the LC perspective holistically aids decision support and increases the potential for mitigating the lifecycle impacts of livestock production systems.

The FAO Livestock Environmental Assessment and Performance (LEAP) Partnership developed a reference guideline on water footprinting for livestock production systems and supply chains [7]. The guideline informs assessment and decision support on both water productivity and environmental performance of livestock systems, focusing on the consumptive (quantitative) aspect of water use and associated water scarcity impact (water scarcity footprint). Degrative (qualitative) aspects are out of its scope, and it refers to other guidelines in line with ISO 14046 [8] and ISO 14040 [9] to evaluate them via other impact categories, namely eutrophication, acidification and ecotoxicity (e.g., FAO-LEAP on nutrient flows, [7]). Thus far, no guidance has been provided by FAO-LEAP to assess ecotoxicity impacts associated with livestock production.

The water productivity assessment must inform about the amount of water required to produce the livestock product (e.g., tonne product m^{-3} water, economic revenue m^{-3} water or their reciprocal in a life cycle inventory, LCI), including not only the water contained in the product but also all the water consumed directly in the production system (farm) and indirectly (supply chain, e.g., off-farm feed production). There are two distinct flows which must be quantified and (following ISO 14046) be reported separately, namely, the consumption of precipitation, which is a determinant in agrifood products (also called green water) and the consumption of ground and surface water including all freshwater flows (also called blue water). However, due to lack of consumption measurements and regionalized estimates, among other reasons, a water productivity assessment often only covers blue water consumption [10].

The environmental performance of water productivity should quantify the potential impacts related to water scarcity. The FAO-LEAP guidelines [7] recommend operational methods for blue water consumption only, as no consensus-based method exists to characterize the impact of green water consumption. Due to the aforementioned uneven distribution of freshwater, consumed water needs to be normalized to the available water in a given geographical context when assessing the (blue) water scarcity footprint. To do so, a geographical border needs to be defined, with the water basin being the most accepted option as it functions as a land unit for water management with often a reasonable data accessibility. The latest frameworks and methods for assessing water consumption-related impacts refine the assessment of water consumption [11,12], differentiating the impacts of consuming water from different water sources within a basin. The latter are, however, not yet current practice, and thus were excluded in the FAO-LEAP guidelines [7], which build on existing, operational and widely applied methods. Data gaps can be a determinant in the characterization of blue water consumption. For instance, the EU Product Environmental Footprint (PEF) initiative [13,14] recommends the use of annual national data, whereas the level of regionalization can have a significant impact on the results [15]. While direct water use can be characterized if there are regional characterization factors available, this regionalization should ideally be consistent among all characterized impact data. However, this is not always possible, due to a lack of regionalized datasets, which affects the water scarcity results. For example, when using secondary data to represent the impact of tap water use, there are no regional datasets that represent the impact of tap water in a specific region [16].

Moreover, there are two concepts that need to be differentiated in the context of this study (or any water footprint), namely, water use versus water consumption. Mechanisms by which water can be consumed include evaporation and transpiration, water that becomes part of a product (i.e., milk water content), and runoff released into a different water basin or the sea. Not all the water used is being consumed; the remainder, in absence of better data, is usually assumed to be returned to its basin of origin. Therefore, water productivity can be calculated based on consumed water (i.e., the part of the used water that does not return to the same basin).

The FAO-LEAP guidelines [7] are a useful toolkit to thoroughly plan a water use assessment that considers the specificities of livestock production systems, building on existing water use standards and methods. However, when applied in real case studies, challenges, gaps, and limitations may arise. In this context, the aim of this study is to expose the challenges that were encountered when assessing water consumption-related impacts of a cow milk production system in Catalonia (northeastern Spain). The assessment encompassed water scarcity and degradative impacts, thus representing a comprehensive water footprint according to ISO 14046. However, as the focus of this special issue is on water consumption impacts, this paper mostly refers to this part of a comprehensive water footprint. In the next sections, we first explain methodological details and results of the case study. We then focus on the water consumption-related impacts and list and discuss the challenges and gaps that we faced to quantify the water scarcity footprint of the studied system. With the findings of this research, we urge the regional administrations of water-scarce areas to encourage real measures of water use at farm level (thus, improving inventories), an advancement of the best available techniques to reduce competition for water use in livestock production, and for the industry to take responsibility over the water footprint of their suppliers. The choice of PEF as a framework for the assessment comes from the overarching objective of the study, which was to test the PEF guideline in a Mediterranean context.

2. Materials and Methods

2.1. Goal and Scope Definition

The goal of the study was to assess the water footprint of a dairy cow milk production chain in Catalonia (northeastern Spain), comprehensively encompassing both quantitative and qualitative aspects, as per ISO 14046 [8]. The system assessed was a conventional, intensive management, characterized by using a combination of commercially purchased compound feed and fodder grown at the farm, which is the most common milk production system in this area. Three farms with slight differences in their management practices were selected in the study area. The cow breed of the assessed farms was Holstein Friesian, the most common in Catalonia and also in Spain, where 96% of milk farms, although only 49% of mixed-meat and milk farms, have this breed [17]. The size of the studied dairy farms ranged between 80 and 250 animal heads. According to 2022 data from the Department of Climate Action, Food and Rural Agenda of Catalonia (DACC), around half of farms in Catalonia had a census of fewer than 100 cows, which together produced half of the milk produced in this region. The average number of cows per farm in 2022 was 194 [18]. The scope of the study was from cradle to distribution gate. Thus, the stages included raw milk production at the farm (n = 3), transport of raw milk to processing plants (industry, n = 1), and transport from processing plants to the distribution centres of supermarket chains and markets (Figure 1). The functional unit used to describe the performance delivered by the system was 1 tonne of fat- and protein-corrected milk (FPCM), as recommended in the Product Environmental Footprint Category Rules (PEFCR) for dairy products [19].

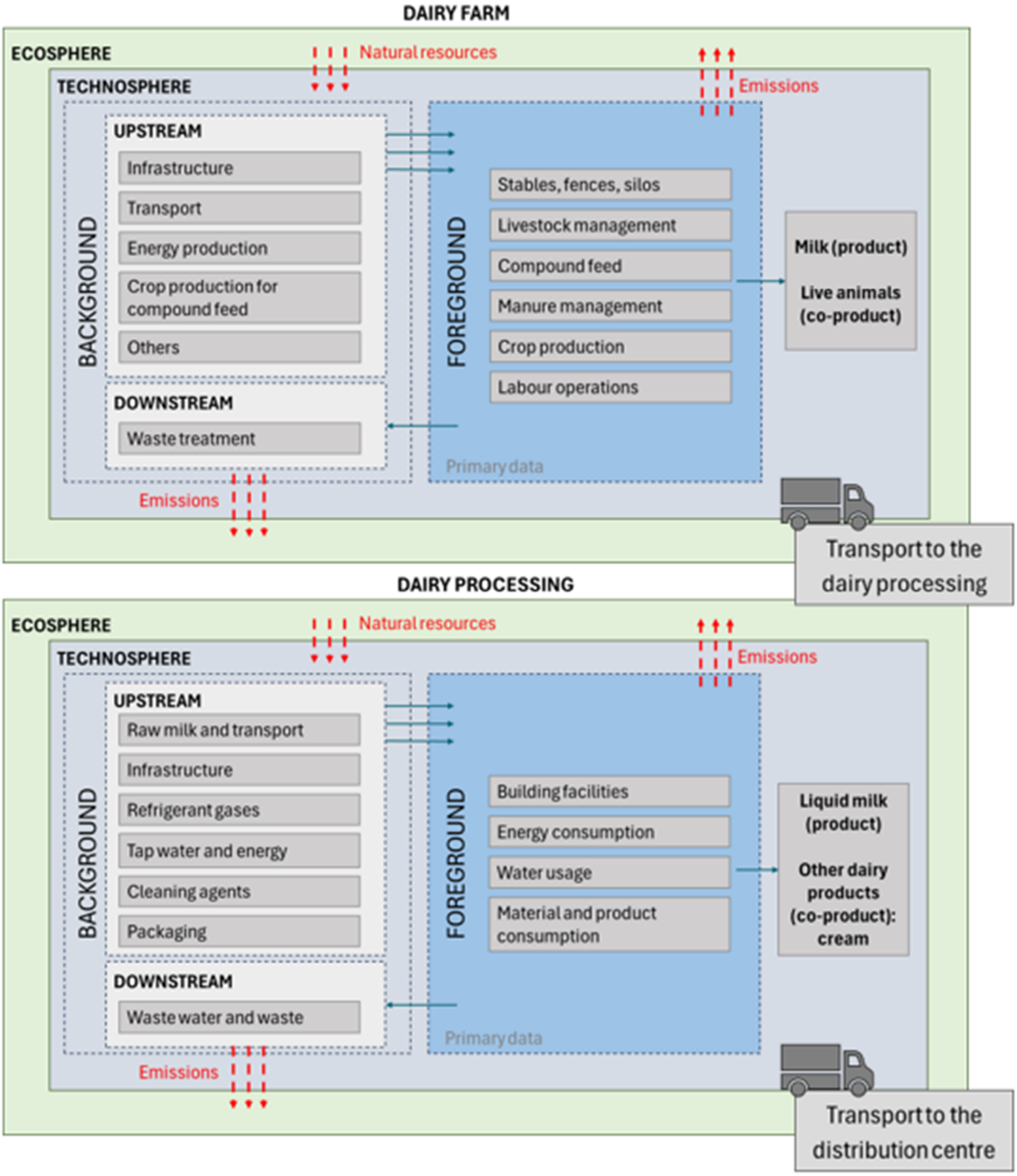

Figure 1. Flow diagram of included stages in the studied system and detail of the system boundaries for the farm and the dairy processing stages. Entry red arrows indicate resources from ecosphere to technosphere. Exit red arrows indicate emissions from background and foreground processes to the ecosphere. Blue arrows indicate the flows between foreground and background, as well as the final product from the studied system.

2.1.1. Modelling Choices and Data

An attributional LCA focused on water-related impacts was performed using the SimaPro 9.1.1.7 software [20]. Primary data, representative of the reference year of the study, were collected from three farms and from a dairy processing plant, including packaging and distribution (thus, transport to market and supermarket distribution centres). To account for the water footprint of the raw milk, impacts from the three farms included in this study were weighed according to their annual production.

Questionnaire-based interviews were carried out to collect primary data along the production chain. At the farm (including fodder grown at the farms), data were averaged for the reference years 2019 and 2020. Data collected for transport and the milk processing industry corresponded to the reference year 2020. Water used in the foreground system at the farm included irrigation water for fodder grown at farms, cleaning water, animal drinking water and water used for animal cooling during the hottest months. Only one of the three farms had a thorough accounting of the used water for each process, aided by water counters installed in the facilities. For the other two farms, estimations needed to be made based on water-pump flow rates, time, and frequency of use. Wasted cleaning water and wasted drinking water flowed to the slurry pond where it was diluted and used to irrigate the farm crops. Water used in the (foreground) industry stage included all the tap water used for processing, cleaning, and refrigerating. Recording of this process input at the industry stage was accurate, thanks to the availability of bills. Secondary data were retrieved from the Ecoinvent 3.6 database [21] and Agribalyse 3 [22], adapted to local conditions when possible (e.g., average transport considering the average number of trucks for each Euro emission standard [European emissions legislation] for the freight transport in Spain, by weight). Background data included all indirect water use at all stages, for example, for producing, cleaning, and transporting all goods needed in the included stages (farm, transport, and industry), such as diesel, vehicles, electricity, packaging, or waste management. The most relevant indirect water to be considered was the water used in the irrigation of the ingredients for the animal feed.

Flows contributing to water degradation at the farm stage included emissions from field manure application, which infiltrates down to the aquifer and eventually reaches natural water bodies, degrading the environmental quality. This can be addressed in a PEF-compliant LCA study by considering the impact of waterborne emissions in other impact categories (see Section 2.1.2, for details) and eventually leads to biodiversity loss (not currently quantified as there was no consensus-based method recommended by the PEF guidelines). In the milk processing industry, elementary flows include the treatment of wastewater. This wastewater can be treated at the plant, or it might go to a municipal sewage treatment plant, depending on the case. To account for this impact, a proxy was used as recommended by the dairy PEFCR [19], applying a correction factor (dilution factor) to account for the increased Carbon Organic Demand (COD) from the dairy wastewater.

2.1.2. Selection of Impact Categories

Consistent with the scope, relevant impact categories related to water consumption and degradation were assessed at the distribution gate using the characterization methods recommended by the PEF guidelines [14,23] and, for water consumption, recommended by the FAO-LEAP guidelines ([7]).

Accordingly, the blue-water scarcity footprint was assessed using the Available WAter REmaining, AWARE, method [24]. AWARE represents the relative availability of freshwater in an area once demand (including human and aquatic-ecosystem requirements) has been met. The range of the AWARE indicator is 0.1 to 100, with lower values indicative of lower water scarcity. The spatial and temporal scales on which AWARE factors were calculated were the water basin and monthly, and aggregations at country, and/or annual level and for different water uses, were also derived. Direct water use (foreground) at all stages was characterized using the country annual average AWARE characterization factors for unspecified water use following the PEF guidelines [23]. A sensitivity analysis was carried out to compare these results with those using AWARE annual factors at the water basin level.

Regarding degradation, the impacts on freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, and acidification were assessed [25]. Waterborne emissions from ionizing radiative elements (for example, from radioactive waste from the use of nuclear energy), which are assessed in the ionizing radiation impact category, and human toxicity impacts, were also included in the assessment so as to be ISO 14046 [8] compliant, which requires the assessment of all environmentally relevant aspects related to water. Table 1 describes the relation of these impact categories to the water use, describing the problem each of them addresses and the model used to characterize the impact for each of them. All emissions from background and foreground processes were considered in the characterization of these impact categories. The most important substances contributing to water pollution were the following: nitrates (marine eutrophication) and phosphorous (non-cancer human health and freshwater eutrophication), mainly from the production and application of fertilizers for crop production and from manure management, as well as emissions due to the production and use of pesticides (toxicity-related categories) for crop production.

2.1.3. Allocation Approach

Regarding system multifunctionality, emissions from cow manure used as fertilizer on field crops from the farm and used to feed the animals were allocated to the field crops. Emissions included are those from manure storage, transport, and field application. The rest of the manure was considered as a residual product (by-product), and therefore its burden was allocated to raw milk produced on the farm [19].

In relation to the production of calves, those that were sold to beef fattening farms were considered as a co-product. Allocation factors for animals and milk were computed as follows: upstream burdens were shared between raw milk and live animals at the farm gate, based on the biophysical allocation method [26] adapted from the International Dairy Federation [27] recommended by the PEFCR for dairy products [19]. The farm-specific fat and protein values (between 3.69 and 3.8% for fat content and 3.09 and 3.3% for protein content) to calculate the mass of FPCM sold per year, and the farm-specific live weight of all the animals (bull calves, culled mature animals and calves sold to fattening farms) to calculate the mass of live weight per year, were considered for calculating the milk allocation factor. In this study, one of the farms surpassed the 3% BMR threshold. Consequently, a biophysical approach based on net energy needs (therefore, including energy needed for maintenance and activity) for milk production and animal growth [26] was used, instead of marginal net energy (which only includes energy directly related to production [27]).

At the dairy processing industry, the impact of the upstream burden was shared by mass allocation between the different co-products (cream and liquid milk in this case) depending on their dry matter content, following the PEFCR for dairy products [19].

Finally, regarding milk waste at the industry stage, the impact of milk waste disposed of with wastewater is considered and distributed among the different co-products. However, milk sent to another industry for its use as an input (e.g., at a bio-waste treatment plant to produce energy), but not to produce dairy products at the processing plant (e.g., milk with lower quality than required or milk that has been used for quality analysis) was considered as a co-product, and its impact was allocated to that of the industry using it [19].

2.2. Life Cycle Inventory Analysis

Farm inventory data (Table 2) were collected to calculate the environmental impact of producing raw milk at the farm gate for three different farms representative of the studied system:

Table 1. Impact categories and models from the Product Environmental Footprint methodology [28] used in this study.

Impact Categories	Environmental Problem Addressed	Recommended Default Impact Model
Water use	Water is a vital resource for life and of limited renewability. The impact category addresses the mismatch between freshwater demand and availability in areas and periods of the year of high demand and low availability. Lack of water may affect humans and aquatic and terrestrial ecosystems.	Available Water Remaining (AWARE) model [24,29]
Eutrophication, aquatic freshwater	Related to nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland, which accelerate the growth of algae, zooplankton, and higher aquatic plants in marine water and freshwater. The degradation of organic material consumes oxygen, resulting in oxygen deficiency, reduction in the water quality and, in some cases, death of flora and fauna. To assess the impacts due to eutrophication, two EF impact categories are used: eutrophication, freshwater; and eutrophication, marine.	EUTREND model [30] as implemented in ReCiPe 2008 [31]
Eutrophication, aquatic marine		EUTREND model [30] as implemented in ReCiPe 2008 [31]
Ecotoxicity (freshwater)	Addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and functioning of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem, causing mortality, mutations, reduced growth, etc.	USEtox model, [32]
Acidification (soil and water)	Addresses impacts due to acidifying substances in the environment. Emissions of NOx, NH_3, Sox and strong acids into the air lead to the release of hydrogen ions (H^+) when the gases react in the atmosphere. When depositing on soils, protons contribute to the acidification of soils when they are released in areas where the buffering capacity is low, which may lower the pH, causing leaf damage and decline in forests. Lakes are also exposed via leaching from soils.	Accumulated Exceedance [33,34]
Ionizing radiation	Accounts for the adverse effects on human health caused by exposition to human-made sources of radiation, like nuclear power generation and construction materials. It is important in studies looking at a significant contribution of nuclear energy to the regional electricity mix. Groundwater can be an important pathway through which radionuclides from stored wastes can reach the biosphere [35], justifying its inclusion in a comprehensive water-footprint assessment.	Human health effect model as developed by [36,37]
Human toxicity, cancer	It addresses adverse health effects on human beings caused by the intake of toxic substances through the inhalation of air, food/water ingestion, and penetration through the skin—insofar as they are related to cancer. Human exposure to toxic substances can occur through the ingestion of water (untreated surface freshwater), and the intake of fish from marine or freshwater, for example.	USEtox 2.1. Model [32]
Human toxicity, non-cancer	It accounts for the adverse health effects on human beings caused by the intake of toxic substances through the inhalation of air, food/water ingestion, and penetration through the skin—insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation. Human exposure to toxic substances can occur through the ingestion of water (untreated surface freshwater), and the intake of fish from marine or fresh water, for example.	USEtox 2.1. Model [32]

- Farm 1: family dairy farm. Animal heads: 33 calves, 30 heifers, 73 mature females. Breed Holstein Friesian, commercial milk rate of 12.7 tonne a year per productive animal. Own crops, 34 hectares (fodder 521 tonne per year) and compound feed (unweaned calf: 22.5 tonne per year; dry cows: 3.6 tonne per year; lactating cows: 278 tonne per year);
- Farm 2: dairy experimental farm. Animal heads: 56 calves, 57 heifers, 119 mature females. Breed Holstein Friesian, commercial milk rate of 11.5 tonne a year per productive animal. Own crops, 70 hectares (fodder 1539 tonne per year) and compound feed (unweaned calf: 109 tonne per year; dry cows: 101 tonne per year; lactating cows: 529 tonne per year);
- Farm 3: family dairy farm. Animal heads: 18 calves, 18 heifers, 59 mature females. Breed Holstein Friesian, commercial milk rate of 6.2 tonne a year per productive animal. Own crops, 41 hectares (fodder 573 tonne per year) and compound feed (unweaned calf, dry cows, lactating cows: 72, 24, and 180 tonne per year and farm, respectively).

Regarding transport inventory data, there were two main processes considered in the foreground. These were the transport of raw milk from the farm to the liquid milk processing industry, and the transport of the final product (liquid milk) to the supermarkets and distribution centres (which added up to around 30,569 and 24,571 thousand tonnes per kilometre (tkm), respectively).

The data from the processing included the amount of raw milk provided by the farms. Although, not compulsory according to the PEF guidelines, due to their low contribution, the infrastructure from the dairy facilities and cleaning agents was also included. The materials, production, transport, and waste management related to the packaging were another process to be considered. Energy, which in this case was electricity, was adapted to the regional electricity mix. Water consumed included that used for cleaning and processing. Refrigerant gases were also considered. Finally, there was the treatment of waste when it was not recycled (such as plastic, cardboard or wood) and the treatment of wastewater. Allocation between two co-products was carried out, as cream was also produced in the processing plant. The dry-matter content of the cream produced at the milk processing plant was 42%, while milk dry-matter content was 10%, according to primary data from this production stage. To calculate the final impact, the milk and cream waste (1.86% and 1.70% of the total production, respectively) were also considered as a co-product, as they were collected and used for energy production by an external company. Therefore, and considering the total output per year of both co-products (which was around 223,775 thousand litres of milk per year and 15,596 thousand litres of cream per year) and the by-products (milk and cream waste) that were valorised, 75.9% of the total impact was allocated to the milk, the remaining impact being allocated to the cream and to the milk and cream waste for energy production. These were all primary data.

Special attention was given to the data collection for water used at the farm. In this study, water extracted to be used directly at the farm for drinking, cooling, and cleaning, was assumed to not be returned to the basin. Thus, all water used (extracted) for drinking, cooling, and cleaning, was assumed to be consumed. This was because all the water not consumed after being used for cooling, cleaning, and animal drinking was channelled to the slurry pond, thereby not returning to the basin from where it was extracted. However, it is often estimated that only a fraction of the used (extracted) water is consumed, and the rest is assumed to be returned to the basin. Average estimates in published databases indicate that when no specific data are available, around 83% of extracted water can be assumed to be consumed in these processes (i.e., 17% is assumed to be released back to the basin in a similar condition as it was when extracted) [38]. Thus, the impact on the farm might have been overestimated in this study in comparison with those data (a 10–30% impact, according to the results obtained).

Table 2. Summary of the main processes from the inventories collected at farm, transport, and processing stages. Litre refers to raw milk produced at farm gate.

Processes by Stage			
Raw milk production (farm)	**Farm 1**	**Farm 2**	**Farm 3**
Commercial milk production rate, tonne animal^{-1} year^{-1}	11,626	10,034	5424
Commercial milk production rate, tonne farm^{-1} year^{-1}	1000	1174	320
Animals, units per farm	164	202	93
Regrowth feed, tonne litre^{-1}	1.96×10^{-5}	7.94×10^{-5}	1.51×10^{-4}
Dry cow feed, tonne litre^{-1}	3.14×10^{-6}	7.33×10^{-5}	5.04×10^{-5}
Lactation feed, tonne litre^{-1}	2.42×10^{-4}	3.84×10^{-4}	3.78×10^{-4}
Fodder [1], tonne litre^{-1}	4.54×10^{-4}	1.12×10^{-3}	1.20×10^{-3}
Energy, diesel kg litre^{-1}	2.69×10^{-2}	1.99×10^{-2}	2.83×10^{-2}
Electricity, kWh litre^{-1}	5.40×10^{-2}	1.82×10^{-1}	3.59×10^{-2}
Water, well, m^3 litre^{-1}	4.77×10^{-3}	4.18×10^{-3}	7.51×10^{-3}
Water, tap, m^3 litre^{-1}	None	6.70×10^{-3}	None
Enteric fermentation emissions, kg year^{-1} litre^{-1}			
CH_4	1.21×10^{-2}	1.25×10^{-2}	2.07×10^{-2}
Slurry storage and management, kg year^{-1} litre^{-1}			
NH_3	3.31×10^{-3}	3.43×10^{-3}	4.98×10^{-3}
N_2O	2.06×10^{-4}	2.03×10^{-4}	3.40×10^{-4}
CH_4	7.89×10^{-3}	3.05×10^{-3}	1.25×10^{-2}
Transport between stages			
Transport of Raw Milk from Farm to Industry, tkm litre^{-1}			1.04×10^{-1}
Milk processing plant			
Water (mainly for cleaning), m^3 litre^{-1}			2.35×10^{-3}
Energy, kWh litre^{-1}			8.14×10^{-2}
Cleaning agents (including sodium hydroxide, hydrochloric acid, lime, iron chloride), kg litre^{-1}			8.68×10^{-3}
Packaging 1 litre volume, units litre^{-1}			7.43×10^{-1}
Packaging 0.2 litre volume, units litre^{-1}			5.50×10^{-2}
Packaging 0.5 litre volume, units litre^{-1}			2.99×10^{-2}
Transport between stages			
Transport of final product (milk) to distribution centres and supermarkets, tkm litre^{-1}			8.34×10^{-2}

Farm differences are due to type of fodder consumed (annual, perennial, etc.).

Direct water use at the farm (inventory) was further separated according to its use, in order to identify main onsite contributors (Figure 2). The main drivers were different at each farm. At dairy farm 1, water was mainly used for irrigation of some of the ingredients of the fodder (in particular, maize) grown at the farm (63%), followed by production of compound feed ingredients (22%), and the water used for drinking (12%) and cleaning at the farm. At dairy farm 2, the water served as drinking water (30%), followed by cleaning and cooling, as well as for producing the ingredients of the commercial compound feed (61%, mainly maize grain). At dairy farm 3, water was mainly used for producing the ingredients of the commercial compound feed (78% mainly maize flour) followed by use at the farm (20%, mainly animal drinking, followed by cleaning).

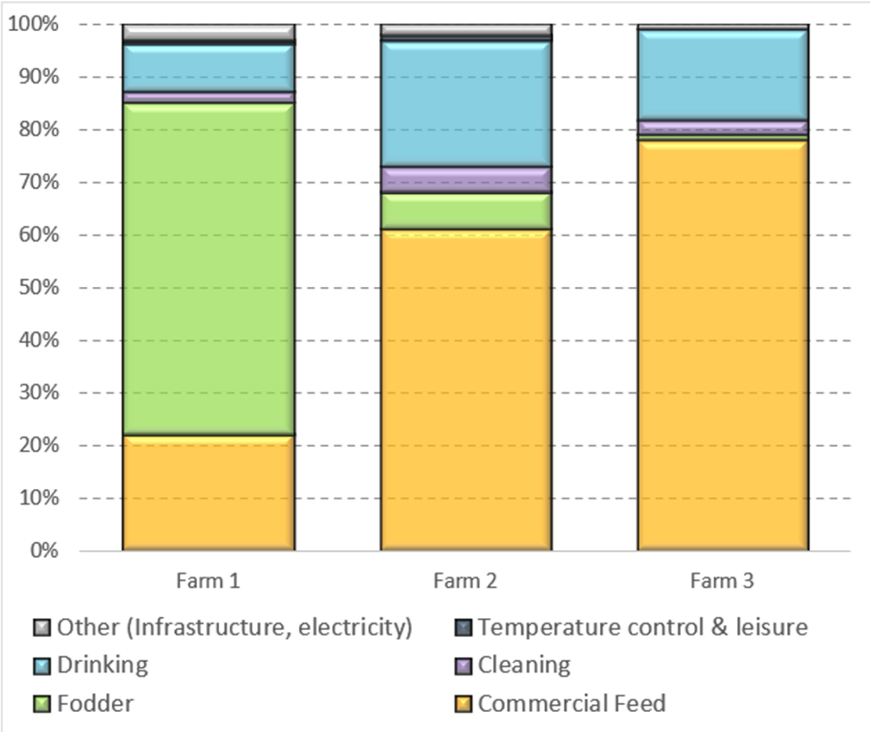

Figure 2. Contribution of each process to the water use inventory at the farm gate for each farm studied.

3. Results and Discussion

In this section, we provide impact results and their interpretation. When performing a water-use and quality-impact assessment following the LCA approach, it is important to consider the quality of the data used for the inventory to properly interpret results. In this context, we also describe the challenges we faced and sources of uncertainty encountered when carrying out the data collection, and the impact characterization phases.

3.1. Water Impacts of Milk Production

Table 3 shows the impact results for each of the water-related indicators and for each farm (per litre of raw milk), as well as the impact at the distribution gate (including transport to the dairy industry, processing, packaging, and distribution to market and supermarket distribution centres, per tonne of FPCM). The last column informs about the benchmark values which, in the context of PEF, refer to the average environmental performance of the representative product sold in the EU market. In general, results were of the same order of magnitude as the European benchmark value [19] for the eutrophication indicators. Results for acidification were almost half the benchmark value (6.51 vs. 12.5 mol H^+ eq $tonne^{-1}$ FPCM). This can be explained using country-specific characterization factors in the foreground system, which are considerably lower compared to other European countries (e.g., for ammonia, the CF in Spain is 0.076 mol H^+ eq kg^{-1} NH_3

emitted, whereas the generic European CF is 3.02 mol H^+ eq kg^{-1} NH_3 emitted [28,33,34]). Acidification is a regional effect that is limited to around the location of the emission source. The sensitivity of an ecosystem towards acidification depends on its capacity to neutralise the input of hydrogen ions. Calcareous (basic) soils present in the area of study are well buffered compared to acidic soils in other regions in Europe, which can explain the lower sensitivity of the Mediterranean ecosystems [33,34]. The contrary happens with the potential impact to the indicator "Water use" which scored considerably higher in the assessed farms compared to European reference values. As shown in Table 3, the characterised benchmark value provided by the PEFCR for dairy products excluding the use stage is 3.11×10^2 m^3 world eq $tonne^{-1}$ liquid milk [19], which is 12% of the value obtained in this study, i.e., 2.64×10^3 m^3 eq $tonne^{-1}$ liquid milk. This can be explained using the annual country-average characterization factor (CF) for Spain (77.7 m^3 eq m^{-3}), which is one of the highest in Europe (e.g., the equivalent CF for Greece, also a Mediterranean country, is 68.4 m^3 eq m^{-3}, and the CF for Europe without Switzerland is 42.9 m^3 eq m^{-3}) [24,28,29].

Table 3. Characterised results of the environmental impact assessment for a selection of categories by tonne of raw milk at farm gate and by tonne of FPCM produced at industry including processing, packaging, and distribution. BMR: ratio between live weight of sold animals and FPCM. Comparisons are only feasible between the farms and between the two last columns. There are not benchmark data for toxicity-related impact categories available in the PEFCR [19].

	Units	Farm 1	Farm 2	Farm 3	Including Processing + Distribution	Characterised Benchmark Values [19]
BMR	%	2.13	3.35	9.47		N/A
		Per tonne of raw milk	Per tonne of raw milk	Per tonne of raw milk	Per tonne of FPCM	Per tonne of FPCM
Acidification	mol H+ eq	5.32×10^0	8.13×10^0	7.85×10^0	6.51×10^0	1.25×10^1
Eutrophication, freshwater	kg P eq	1.70×10^{-1}	1.74×10^{-1}	2.75×10^{-1}	1.98×10^{-1}	1.04×10^{-1}
Eutrophication, marine	kg N eq	4.28×10^0	7.88×10^0	8.61×10^0	5.77×10^0	3.75×10^0
Ecotoxicity, freshwater	CTUe	2.64×10^4	3.53×10^4	3.60×10^4	3.29×10^4	N/A
Water use	m^3 eq	3.15×10^3	2.82×10^3	2.92×10^3	2.64×10^3	3.11×10^2
Ionising radiation	kBq U-235 eq	6.85×10^1	1.34×10^2	8.76×10^1	1.37×10^2	5.63×10^{-2}
Human toxicity, cancer	CTUh	8.02×10^{-7}	7.72×10^{-7}	1.23×10^{-6}	7.83×10^{-7}	N/A
Human toxicity, no cancer	CTUh	3.15×10^{-5}	2.21×10^{-5}	4.39×10^{-5}	2.68×10^{-5}	N/A

3.2. Contribution Analysis at Distribution Gate and at Farm Gate

The main driver of the impact at the distribution gate for the studied milk production system was the raw milk production, which contributed more than 60% to all impact categories included in this assessment (Figure 3). The rest of the impact (less than 20% in all cases except ionising radiation, where it was less than 40%) corresponded to the impact from transport, processing, and packaging of the milk. Therefore, it is at the farm stage where efforts should be focused to improve the sustainability of the final product.

Focusing on the processes that take place before the farm gate, more than 70% of the impact for all analysed indicators came from the production of feed (Figure 4). Another highlighted, contributing process was the consumption of diesel (10–30% in six out of eight impact categories assessing water degradation). Electricity consumption has a significant contribution to the impact category of ionising radiation, due to the Catalan electricity mix, with a high nuclear energy contribution. The water use results at the farm were further separated according to use. This allowed for the identification of hotspots in the production system, for setting a baseline, and for tracking future improvements in efficiency against the initial baseline and other local benchmarks of similar production systems. The direct use of water at the farm represented only 10–30% of the whole impact for the category. Results show the importance of considering, apart from the direct water use, the indirect water consumption also, which aggregates water use and impacts on the locations of life-cycle stages upstream of the livestock farm, providing an accurate account of the water use efficiency and impacts of water use.

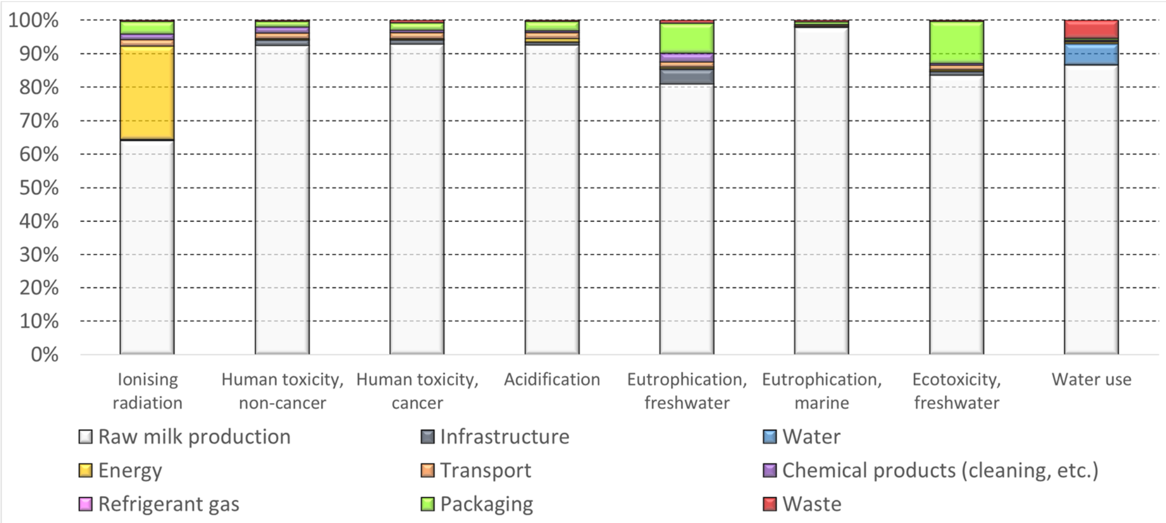

Figure 3. Contribution analysis at distribution gate; Raw milk production is milk produced at farm gate.

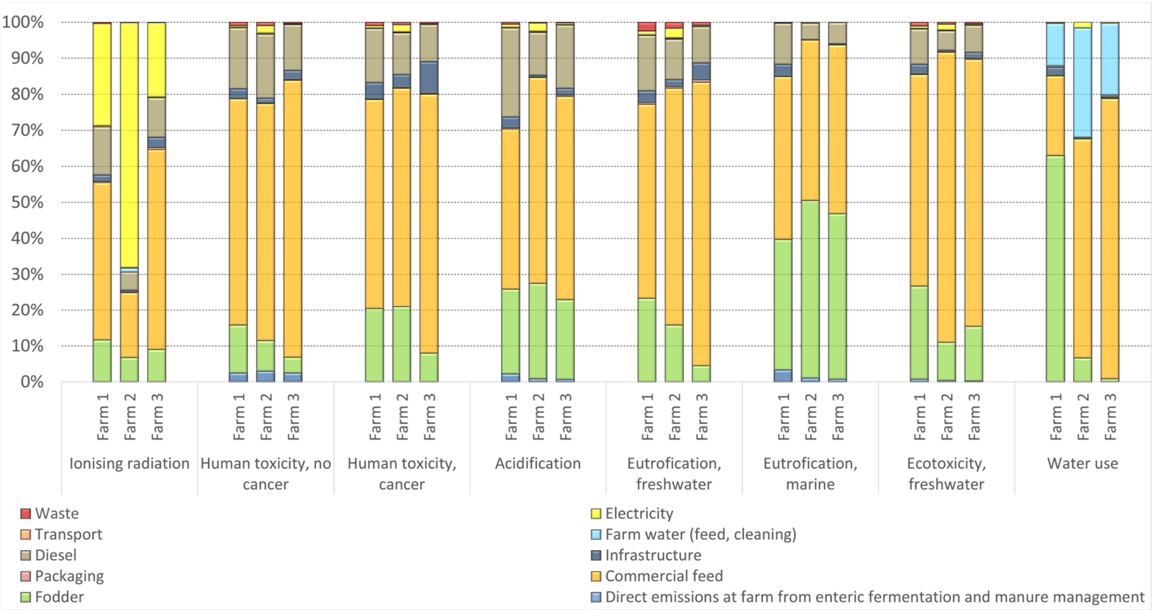

Figure 4. Contribution analysis at the farm gate; in green and orange colour, all the feed-related processes (fodder, commercial compound feed).

The great importance with regard to the water footprint of milk production of the water which is used in irrigation of crops used as feed ingredients (>80% of the impact for most impact categories) is in line with estimates of earlier studies that reported production of feed to be a main driver of the water footprint from milk [25,39]. Water (in)efficiencies of the conveying and irrigation systems are a concern. In terms of crop consumption, there is a risk in considering that inefficient irrigation systems return excess water to the watershed, so it is not used. On the contrary, it is necessary to consider the water (in)efficiencies of transport and irrigation systems. Currently, WFLDB [38] proposes the approach of applying irrigation efficiency coefficients, which depend on the irrigation technique. However, these are fairly general values that correspond to surface, sprinkler, and drip irrigation techniques. In addition, there is also a part of the water which is not consumed by the crop and which is lost by evaporation into the air, called white water. More research is therefore needed to include more irrigation systems (e.g., pivot, buried systems, etc.) and those agricultural practices (e.g., mulching, cover crops, organic fertilisation, etc.) which can lead to water savings.

In this study, the cultivation of maize has the largest impact weight (60–80%), as has also been reported by Mekonnen and Hoekstra [40]. Maize is at times produced at the farm, and at times imported. Globally, the contribution of maize to the water footprint has been estimated to be mostly due to being produced in water-scarce countries, rather than to the large number of imports as with other crops like soybeans [41]. The studied farms are in the Mediterranean basin, where the availability of water is of increasing concern, with two of the farms having their main maize source cultivated on the farm, and maize from the other farm being purchased outside. In line with this demand and given that green water availability is expected to decrease in the study area, maize imports are forecasted to rise in Europe [42]. Therefore, in order to reduce water-use impacts of milk, it would be advisable to include, among others, criteria for selecting the origin of imports based on more favourable water scarcity indices. These results are in accordance with the proven high dependence on virtual water imports in Europe in general, which has been estimated in 11 km^3 of associated virtual irrigation water [41]. In relation to the potential increase in imports, an increase in the use of secondary datasets can be expected. Therefore, the traceability of compound feed ingredients needs to be promoted (geographical origin related to the impact of regionalized agricultural practices and transport, and certifications, for example, related to water footprint, etc.). In this sense, more geographically representative datasets are still needed. The use of proxies increases uncertainty, and adapting existing datasets creates inconsistencies across data used in the inventory.

The Inventory collected included blue water, which can be the water supplied either from the tap (which includes impacts from infrastructure and municipal treatments), regenerated (not the case in the studied farms), or from nature (which can include wells, as was the case in the studied farms and, in some cases, surface water for irrigation). The lack of a registry of primary-water-use data needs to be addressed. Some farms have a thorough water registry. This is often the case in bigger farms that invest in optimizing their efficiency. It could also be the case when all water comes from the tap, as there would be bills, but this is not common practice. The water used at the farm often comes from natural sources such as wells. Despite the conditions of drought and competition for access to water, in many cases there are no water meters used. Furthermore, there could be inconsistencies among the different farms included in an assessment if there are real measures in some of them and estimations in others. The inconsistency can also occur when comparing data across different studies, as modelling choices might not be the same. For example, to a certain extent there is agreement in how to estimate drinking water depending on the animal type and age, and the litres of milk produced by a cow. But the amount of drinking water can also vary according to season and type of feed. For cooling water, if data are not available, water use can be estimated by means of the number of pumps, usage time, frequency, and flow rates. A similar approach can be used to estimate the amount of water used for cleaning. In the case of needing to estimate the amount of water used for crop irrigation, estimation depends on the irrigation system. For example, a similar approach could be used if a pump is being used to move water from its natural source to the crop. If the crop is irrigated by using flooded grooves, measuring those could give an estimation of the amount of water needed. All these estimations increase uncertainty and inconsistencies across inventories and water-use accounting. Therefore, it is necessary to promote better water use registration, for example by promoting the use of water meters and requiring the registration of the water used in the field notebooks. In the meantime, clear guidance on how to estimate these parameters could reduce inconsistencies within and across studies. Our recommendation is that this data collection also differentiates between surface and ground water, as the development of specific CFs to differentiate the impact of using both sources becomes an important research need [11].

Another source of uncertainty is the estimation of consumed water. As explained above, farmers and industry could potentially measure (when a proper registration system is available) how much water is being used in their production stage. However, according to the methodological guidelines [7,19] water consumption is the environmental flow needed to be estimated, which adds uncertainty when accounting for the water returned to the watershed [43]. On the other hand, the inclusion of water use in the water footprint assessment helps to evaluate water saving measures like efficient irrigation systems or drinkers, which reduce water losses. Thus, water use would better reflect the efforts of the farmers to reduce water withdrawals (eco-design). Furthermore, there is more uncertainty regarding where the flows back to the basin go and if they can be reused again. The used water might be returned to the basin having a different quality compared to how it was when extracted. This should be reflected in other impact categories such as eutrophication. Caution should be exercised when only the water footprint is being assessed, as we might be missing environmentally critical information related to the real impact on fresh water. Therefore, we recommend the adaptation of how water use is accounted for, so that both flows, water used and consumed, are considered. Firstly, to prevent unnecessary water withdrawals that could inadvertently modify the properties of water returned to the basin, and secondly, to model the potential environmental impact that this water can have on the basin.

In line with this importance of the irrigation water used in the crops from the feed, the current PEF recommendations, followed in this study, leave out the calculation of the impact due to the consumption of water supplied by rain and stored in the soil (green water), due to lack of available data and an internationally harmonized methodology to characterize its impact. While it has been argued that green water is not considered a withdrawal and, in principle, does not deprive other users [43], the guidelines developed by FAO-LEAP [7] summarized the fact that green water flows need to be considered in the inventory. It also stated that impact assessment only needs to be performed where a livestock production system implies a change in green water flows compared to the flows occurring with the original land use/state [7]. In this context, green water can be of growing importance in future climate scenarios, where precipitation patterns and soil moisture might change for the worse, therefore justifying a rethinking of the feed management, ingredient changes or increasing imports. Knowledge of how much water is used in agriculture in a certain area should include green water, so the sector can be prepared to adapt to future climate scenarios. Facing further droughts in the future, it could be relevant to assess the potential substitution of high green-water-consumption crops for others with lower needs [44].

3.3. Robustness of Results

Regarding spatial representativeness, PEF requires assessments to be carried out at country and annual level [13]. Also, assessments are required to be conducted using user unspecific factors (without distinguishing if the water consumption is for irrigation or for other uses like for livestock drinking, cleaning or industry) [28,45]. A sensitivity analysis was carried out using different levels of spatial differentiation in the AWARE CFs to assess the water scarcity footprint. The recommendation accommodates well to assessing water uses before and after the livestock farm, for which only information at country scale is available at best (e.g., country of origin of feed ingredients and milk exportation to another country). However, for direct uses on the farm, the exact location of the water consumption to be assessed is known, and AWARE CFs with higher spatial detail can be used. In principle, country-level factors come with higher spatial uncertainty, particularly in larger countries and countries with a very diverse hydrology, like Spain, where AWARE factors at regional resolution range between 8.19 m^3 eq m^{-3} (Asturias, northwestern Spain) and 99.54 m^3 eq m^{-3} (Murcia, southeastern Spain). Thus, using smaller spatial units such as regions and watersheds, as the FAO-LEAP guidelines recommend [43], improves the accuracy of results. Therefore, we compared the following three alternative regionalisation levels: (i) country scale CFs [24]; (ii) CFs per administrative region, i.e., sub-national regionalisation [46]; and (iii) CFs per watershed [24].

Results were shown to be sensitive to the spatial scale applied (Table 4). The use of the sub-national level CF instead of the country level one did increase the impact in the three farms proportionally, showing low sensitivity in the absolute result values, but not in the relative results among farms. Using watershed-level CFs when higher spatial resolution is available could reduce spatial uncertainty in the results, as indicated above. However, in this case, farms were less than 10 km apart, and watershed-scale CFs varied from 74.21 m^3 eq m^{-3} (Ter watershed) to 3.44 (Muga-Fluvià watershed) m^3 eq m^{-3}. This resulted in a water footprint 70% greater for farms 2 and 3 than for farm 1, whereas using the country CFs the impact difference between farms was lower than 15%. This important difference between site-generic and site-specific CFs is important and should be understood by practitioners and communicated to the commissioner of the study, and shows the complexity of intricately modelling reality. Due to the complexity of accounting and modelling choices, results obtained can vary significantly. Thus, for a good interpretation and communication of the results, it is important to be transparent in the chosen methodological procedures. It is advisable to provide the absolute values, but with clear recommendations about their relativeness. For instance, in the case of farm 1, the use of watershed CFs could be interpreted as water not being a problem. However, because of the limits of the models, the surrounding conditions, and the administrative context, it would be advisable to be more careful with water consumption.

Table 4. Characterised results of the water-use impact assessment by tonne of raw milk at the farm gate; comparisons using different levels of regionalization of the characterization factors.

Dairy Farms	Farm 1	Farm 2	Farm 3
National CF, Spain (m^3 eq m^{-3})		77.7	
Water use results (m^3 eq ton^{-1} raw milk)	3.15×10^3	2.82×10^3	2.92×10^3
Regional CF, Catalonia (m^3 eq m^{-3})		80.86	
Water use results (m^3 eq ton^{-1} raw milk)	3.24×10^3	2.86×10^3	2.95×10^3
Watershed	Muga-Fluvia	Ter	Ter
Watershed CFs m^3 eq m^{-3}	3.44	74.21	74.21
Water use results (m^3 eq ton^{-1} raw milk)	1.01×10^3	2.49×10^3	2.90×10^3

AWARE characterization factors are available at different temporal and spatial scales (month/year, watershed/country) as well as water use types (agricultural/non-agricultural). Although PEF does not recommend AWARE specific CFs by water use type (agriculture/non-agriculture), or on a monthly scale and at basin level for reasons of applicability, a monthly analysis with regionalized factors could provide more detail of the situation of each farm when data are available. This has been considered as a trade-off between precision and applicability [25]. Regionalized databases are being developed that will facilitate this work towards regionalization [47,48]. When using watershed-level CFs, there is a potential boundary effect. In this study we showed two farms located a few kilometres from each other with very different water footprint results when using watershed-level CFs. These differences in CFs from both watersheds can be due to differences in flows and water demands at the watershed level, but this big difference in results proved difficult to communicate, as there were no specific farm location data to prove these apparent differences in climate (i.e., rainfall) and environmental (i.e., ecosystem demands) conditions among these farms. Environmental conditions in real life can change gradually, whereas CFs are discrete values allocated to unit areas (here, watersheds). In cases where close farms are in two adjacent watersheds with very different CFs, the uncertainty introduced by the boundary effect of the spatial unit might cancel out the gain in accuracy through using watershed-level CFs.

Thus, the question that arises is the level of spatial detail of CF which is more suitable for the assessment: watershed, regional, or some type of average. In principle, it would be desirable that CFs are not too sensitive to small changes in spatial boundaries. In the literature, methods have been suggested to deal with this problem, called the modifiable areal unit problem (MAUP), which arises when continuous spatial phenomena are modelled with discrete geographic units [49]. However, techniques to solve MAUP have been rarely applied to spatially resolved LCA, including AWARE. We did not find any guidance to handle this problem in a case study that needs a relatively rapid and systematic solution. Our recommendation would be to do as we did and apply the suite of CFs at the country, sub-national and watershed level and raise a precautionary flag in the communication of results. This boundary effect is linked to the underlying spatial uncertainty of the drainage basin area used in spatially distributed CFs. This is the case for the method used in this study, AWARE. The spatial base data is DDM30 [50]. The development of regionalized AWARE factors for specific areas/countries giving values that are still potential (meaning not real) can improve the impact assessment regionally, but the comparison of impacts of processes happening in different areas of the world would be obstructed by the potential inconsistency of the assessment. Thus, further development of the characterization of this impact is needed if we want to achieve good quality assessments with homogeneous criteria. Therefore, efforts must continue towards finding ways for computing the impacts of water withdrawals from, and returning to, different water compartments.

3.4. Water Use Terminology

Overall, an agreement on terminology is still needed, as terms are used interchangeably in some guidelines and regulations. The impact category that aims at representing the impact from the use of water in relation to the available water remaining per area in a watershed, after demand from humans and aquatic ecosystems has been met, is referred to by the PEF guidelines as "Water Use" [13,14]. This name can be confusing in some contexts. Water use as defined by ISO 14046 [8] represents the "use of water by human activity", while the term "consumed" is employed to describe the water that is removed from, and not returned to, the drainage basin from where it came [8]. There is another term used when referring to water consumption, "consumptive water use" [7], which is often simplified to "water use" [7], causing potential misunderstandings across the scientific community from different backgrounds. Water footprint is described as the metric used to quantify the environmental impact related to the consumed water. Therefore, the direct quantification of the amount of water used, or even the calculation of the water consumed by an activity, process or product should not be defined as water footprint, as it is not accounting for its environmental impact but defining the inventory.

The method recommended by the PEF initiative [14,51], AWARE [24], recommends the estimation of consumed water to calculate the magnitude of the impact caused, excluding the water returned to the drainage for this impact category assessment. Both AWARE [24] and the Blue Water Scarcity Index [52] are defined as indicators of water "scarcity" and are included as recommended methods by the FAO-LEAP guidance [7]. Thus, even though one uses the water used and the other the water consumed, both characterize the magnitude of the impact of this amount of water (inventory) in relation to a reference of available water, the calculation of which varies in both methods.

4. Conclusions

In a context of growing concerns in Mediterranean (and other semi-arid) areas regarding water availability for agricultural use, this paper aims at assessing the water-related impact categories of the milk production chain in Catalonia, applying a life-cycle perspective.

In relation to the environmental assessment results, the farm stage was the major contributor to the water footprint at the distribution gate, and feed was the major contributor at the farm gate. This feed was in some cases dominated by the fodder and in other cases by the commercial feed ingredients, depending on the ingredients or crops that were irrigated (mainly maize). This contribution was followed by water used at the farm (mainly animal water intake, followed by cleaning water). Considering compound-feed ingredients with a lower water footprint, together with a more efficient use of water and research into slurry treatment for its use as irrigation and cleaning water (without compromising safety and health) could help reduce this impact.

Regarding the challenges encountered when applying the PEF methodology to our milk production system, the application of policy measures that encourage reduction in water use (e.g., efficient irrigation systems and other best available techniques) will not be reflected in the environmental assessment outcome if we are using water consumption as the only indicator. This relevant information on consumed-water impact assessment needs to be accompanied by the information related to water use. Therefore, water impact results should be considered precautionary, due to the need for further development of models/factors that allow the performance of LCIA to be consistently regionalized, both in the foreground and the background data of the system.

Traceability and transparency along the production chain remain challenging. On the one hand, it is important to account for how the import of raw materials (thus, the geographical origin of crop production for animal feed) can impact the availability of water resources in areas different to the region where an agrifood product is being produced and where it is being consumed. This could be addressed with the collaboration of the industry, by consistently tracing where their inputs come from. On the other hand, it is important to encourage the improvement of the PEF profile of products by favouring raw materials with lower water footprint. This could be encouraged by implementing communication measures using scientifically based methodologies for food products to support informed consumer choices.

Finally, water is a crucial and increasingly worrying aspect because of climate change in Mediterranean regions with increasingly scarce, but more intense, rain. It is thus necessary to work towards policies that facilitate water accountability, and control and reduce water use along the production chain through the use of water efficiency measures. To support this, water-footprint methodology must work towards a multi parameter model that takes into account water-use savings rather than focusing only on consumption values.

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