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Evaluation of the spatio-
temporal future effects of
climate change on the
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TESIS DE DOCTORADO

**EVALUATION OF THE SPATIO-TEMPORAL
FUTURE EFFECTS OF CLIMATE CHANGE ON
THE EUROPEAN DAIRY SECTOR**

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SUMMARY

Climate change is already a reality, and its global effects are expected to worsen. To prevent increasingly and irreversible climate change impacts, limiting global warming to 1.5 degrees Celsius has been a goal of global initiatives, such as the Paris Agreement, and European initiatives, such as the Green Deal. This goal implies reaching net zero greenhouse gas (GHG) emissions globally by 2050.

Worldwide, the dairy sector has been recognized as an important source of GHG emissions, principally due to the large contribution of methane, and other environmental impacts related to water and land. In this context, the European dairy sector has been doing efforts to reduce its environmental impact, and in line with the mentioned initiatives, it has set ambitious environmental targets for 2050. It aims to turning into a climate-neutral (i.e., net-zero GHG emissions) sector while promoting efficient land and water use.

Life Cycle Assessment (LCA) is a comprehensive methodology for evaluating the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to disposal. It has been a widespread methodology that has supported the dairy sector as it has provided a comprehensive assessment of the environmental impacts of dairy farms, allowing the development of strategies to mitigate those impacts and track their progress over time.

The LCA methodology has supported the dairy sector in its transition to ambitious environmental targets for 2050. Nevertheless, such transition is affected itself by evolving climatic conditions. Thus, it will be challenged by climate hazards posed by climate change. All climate scenarios used for 2050 forecast more intense climate hazards, while presenting significant variations across the five biogeographical regions present in Europe (i.e., Atlantic, mountain regions, northern Europe, continental and Mediterranean). Climate hazards interact with ecosystems and threaten the dairy value chains, mainly the primary production (i.e., raw milk production and required crop provision) as it is the most vulnerable stage to climate change. Related to primary production, climate hazards cause biophysical impacts as they have an effect on both the biological (i.e., dairy cows and crops) and physical systems (i.e., water, soil, and atmosphere). As a consequence, these impacts have an effect on the performance and food safety of dairy farms, modifying the environmental impact per amount of raw milk produced. Ultimately, more resources are required to achieve the same amount of milk produced.

In order to avoid climate hazards and their uneven biophysical impacts, adaptation strategies are required, and they need to address the specific climate hazards present on a particular dairy farm. However, they might require material and resources to operate (e.g., energy and water) and, as a consequence, release emissions, also altering the milk environmental cost. In this sense, adaptation strategies need to be carefully evaluated to identify possible trade-offs between environmental costs and benefit. The design of adaptation strategies should pursue adapting to climate change while leading to lower environmental impact to enable the dairy sector's pathway towards the environmental targets by 2050.

There are large number of climatic and non-climate hazards (e.g., technological improvements, market shifts, regulation transition), which interact with one another, that modify each item of the Life Cycle Inventory (LCI). Thus, constructing an LCI that takes into account the future effects of climate change is a complex task as different data sources (i.e.,

simulation models, tools, software, and literature) with different computational requirements are required to quantify changes in the LCI. In addition, the complexity is associated to the uncertainty existing in the employed climate data and models as well as the lack of information and climate projections.

To manage the uncertainty of the data sources and the complexity of the LCI estimation task, a toolbox, which can be embedded into the LCI phase of LCA, is proposed to generate hypothetical LCIs that account for the biophysical impacts of climate hazards at the dairy farm level across different European regions and climate scenarios. Along this thesis, the toolbox is also tested on two dairy farms located across two biogeographical regions with contrasting climate conditions (i.e., the Mediterranean and Northern Europe). As a result, two hypothetical LCIs are obtained, making it possible to proceed to the LCIA phase and conduct a contribution analysis mainly to identify the most significant climate hazards among those analysed. The integration of different data sources results promising to enable the generation of useful information on this landscape full of complexity and uncertainty. This research seeks to generate valuable information for the European dairy industry, so that it can support the European dairy industry in anticipating the biophysical impacts of climate hazards by 2050 and facilitate decision-making to strengthen adaptive capacity to climate change while fulfilling the environmental targets by 2050.

This thesis is composed of 7 chapters that are briefly described below:

Chapter 1 is an introductory section that contextualizes the landscape in which the thesis is built. It provides clear understanding of the interaction between the effects of climate change along dairy value chains and their environmental impacts. From there, connections are qualitatively captured between climate hazards, their biophysical impacts, and their effect on the environmental performance of the dairy value chains and placed in a matrix. It allowed to identify the most relevant climate hazards across the dairy value chains based on their effects on their environmental performance. As a result, seven climate hazards were identified as the most relevant: water stress, floods, crop pest infestation, climate variability, cow heat stress, cow diseases and product safety risk. It is possible to observe that water stress might change ground and surface water availability, leading to a potential variation on the GHG emissions and water use variation due to the water use from non-renewable sources. Floods, both permanently and flash, together with many other climate (i.e., water stress, climate variability and crop pest infestation) and non-climate hazards, lead to changes in the geographical distribution of crops and, consequently, transportation distances might change. Besides, crop-growing areas changes can also modify the environmental impact of raw milk since agroecological practices vary throughout countries. Crop pest infestation will lead to an additional use of pesticides by farmers as a measure to cope with pests' pressure. Climate variability is another climate hazard analysed at this stage that led to changes in the crop yield, either positively or negatively, as well as changes in the geographical distribution of crops. Cow heat stress is another climate hazard described and linked to variations in the dairy farm's environmental performance. Heat stress leads to a reduction of the cow milk production, which is translated into raw milk losses compared to a baseline. In order to relief cow heat stress, heat abatement systems are required; however, they require energy and water, leading to a modification of the GHG emissions and water use at the dairy farm. Finally, cow disease is another climate hazard that is also linked to raw milk losses. Bovine mastitis is considered the most common disease across dairy farms globally. It alters the raw milk quality, safety and reduces cow's milk yield, which is also translated into raw milk losses. Moving to the rest of

the life cycle stages (i.e., dairy factory, distribution, retail, and consumption), the climate hazards identified here are also related to product safety risk. 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, which is directly linked to potential food losses and waste. From this qualitative analysis, it is possible to see that climate hazards and their biophysical impacts do affect the environmental performance of dairy value chains, and then, the next step is to quantify these climate hazards and changes in the environmental performance.

Chapter 2 gives an overview of the methods used in this thesis to estimate changes in the environmental performance of the dairy sector under the future effects of climate change.

The chapter is divided into three sections and in each section LCA, Risk Assessment (RA), and Input-Output (IO) tables are described separately first and then how they were combined with one another to achieve the objective of this research. The methods are implemented in the context of the primary production stage (i.e., dairy farm and crop production), which is the main contributor to climate change but also the most vulnerable to global warming based on the results from Chapter 1. The integration of the three of them results in a promising approach to ensure food safety and support the environmental targets for 2050 in a climate change era.

LCA is a powerful methodology to estimate the environmental impact of dairy farms. However, the estimation of food waste has been often disregarded or not accounted for with the required level of detail in the LCI, which can result in underestimating the environmental impact of the produced milk. The integration of RA into LCA provides a transparent and detailed estimation of the milk lost at dairy farms while distinguishing between regions that may be affected differently by climate change. The integration of LCA and RA aims to examine whether ensuring food safety leads to higher environmental impact and vice-versa. The integration can detect and avoid trade-offs when seeking to reduce food safety risks and food losses and waste while reducing the contribution to climate change and other environmental impacts along dairy value chains.

In addition, some information such as the origin of the off-farm feed used on the dairy farm is sometimes not available. And a detailed analysis is required since cows' feed is one of the main contributors to the total environmental impact at this life cycle stage. The use of IO tables, such as FABIO (Food and Agriculture Biomass Input-Output), allows to trace the origin of the crops, and then, it is possible to obtain site-specific information on them such as their yields, which are expected to change unevenly across the world.

Chapter 3 focuses on estimating the current and future raw milk losses caused by bovine mastitis across three biogeographical regions in Europe and climate scenarios by 2050 by implementing RA. The resulting percentage of annual raw milk losses is then incorporated into a theoretical LCI built in Chapter 4 to estimate the environmental cost of the raw milk lost due to mastitis. This task provides an illustrative example of how to evaluate the impact of climate change on cow disease and ultimately on the dairy value chain. Bovine mastitis is considered the most common disease present across dairy farms all over the world. Mastitis is induced by several pathogenic microorganisms that enter the cow's gland through the teat canal from both, a contagious and an environmental manner. One of the most common pathogens isolated across European dairy farms is *Staphylococcus aureus*. In turn, bovine mastitis increases raw milk losses, which occur in two ways at dairy farms. Indirect raw milk losses represent the milk that cannot be produced as a response of the decrease in the cow's milk yield due to the infection.

Direct raw milk losses include the milk that is discarded as it does not meet the raw milk quality requirements in terms of somatic cell count (SCC).

An exposure assessment model and a stepwise probabilistic model were developed to predict potential raw milk losses linked to a reduction of milk yield and exceeding the *S. aureus* and SCC concentrations at dairy farms. The model included the current and projected temperatures by 2050 reported by the Representative Concentration Pathways (RCP) from the IPCC (2018), where the RCP2.6 was selected as an optimistic scenario with great mitigation efforts, the RCP4.5 as an intermediate scenario, and the RCP8.5 as a pessimistic scenario where no efforts to reduce GHG emissions are made. In addition to climatic parameters, improvements practices were also considered, such as the increase in milk yield per cow due to more productive cow breeds and the reduction in the prevalence of mastitis due to the availability of more effective treatments in the future. The model showed that among the three regions (i.e., Atlantic, Mediterranean, and Continental), raw milk losses ranged from 1.06% to 2.15% in the baseline. However, they increased up to 3.21% in the climate change scenarios when no on-farm improvements were considered. Regarding geographical variation, the highest potential milk losses were reported for the Mediterranean and the lowest for the Continental region. Concerning the fulfilment of the regulatory limits, the mean of *S. aureus* and SCC levels in milk did not exceed them either in any region or scenario. On the distribution tails, nevertheless, the 10th percentile remained above the limits of *S. aureus* in Atlantic and Mediterranean, but not in the Continental region. In addition, it was demonstrated that on-farm improvements have a significant effect on the raw milk losses.

Concerning to the validation of the model, predicted milk losses were compared with values reported in the literature and the estimated values were within the range of the values reported by the literature. Unfortunately, this validation was only possible for the baseline scenario since there are no projections of raw milk losses at a farm level by 2050 across regions.

Chapter 4 proposes and tests a toolbox to estimate changes in the LCI due to the biophysical impacts of climate hazards on dairy farms and their environmental impacts across different geographical and temporal horizons. The climate hazards and their biophysical impacts addressed are the six hazards previously identified in Chapter 1 (i.e., water stress, floods, crop pest infestation, climate variability, cow heat stress, and cow diseases). The toolbox is composed of three modules in which different data sources (i.e., simulation models, tools, software, and literature) were employed to generate the required information for addressing the climate hazards (i.e., water stress, floods, crop pest infestation, climate variability, cow heat stress, and cow diseases) and their biophysical impacts present at the dairy farms.

The first module defines the geographical and climatic context of the case study regions. The second module estimates the intensity of the climate hazards and their biophysical impacts by 2050 across dairy farms under study. The third module collects the quantified percentage changes in the inventory caused by climate change to build the theoretical LCI of the future scenario (i.e., 2050). Then, it is possible to proceed to the LCIA phase and conduct a contribution analysis to identify the most significant climate hazards among those analysed. Here the estimation of annual raw milk losses from Chapter 3 is also incorporated in the construction of the theoretical LCI where it leads to changes of the reference flows. This toolbox is aimed to be embedded into the LCI phase of LCA, as it generates theoretical LCIs that account for the biophysical impacts of climate hazards.

Since the impacts of climate change are geographical and climatic scenarios unequal, the selected data sources must meet two criteria: i) cover different geographical locations and ii) cover different time windows under several climate scenarios. When such type of data was not found, it had to be generated either by placing together existing models or by developing them specifically for the dairy farm under study. For instance, available data sources were used to generate information on the following climate hazards and their biophysical impacts: water stress, floods, crop pest infestation and climate variability. However, no data was available to address cow heat stress and diseases across different regions, temporal windows, and climate scenarios. This type of data was generated by extending in this work available models.

To demonstrate the applicability of the toolbox, it is tested on two case studies featuring two regions with distinct climatic conditions under the SSP2-4.5 scenario: a Spanish dairy farm in the Mediterranean region of Europe and Swedish dairy farm in the Northern of Europe. As a result of the toolbox implementation, raw milk losses caused by cow heat stress and cow diseases are responsible for the rise in global warming potential and water depletion, while crop pest infestation and climate variability are responsible for the rise in land occupation. By integrating already available as well as adapted models, with different levels of complexity and computational requirements, the developed toolbox allows for exploring the possible scenarios that European dairy farms will face and for understanding of how climate change will affect them and their environmental performance.

Chapter 5 identifies site-specific adaptation strategies and evaluates their net-environmental cost to identify win-win strategies, which are recognized for adapting to climate change at a lower environmental cost while ensuring dairy farm production and food safety. To do so, a five-step framework is proposed. The first step prepares the ground for adaptation in which the temporal-climatic and geographical horizons are defined. In line with Chapter 4, two dairy farms located in the Mediterranean and Northern regions under the SSP2-4.5 scenario are defined. In the second step, site-specific climate hazards and their related biophysical impacts are identified and understood. This step is built on the in-depth analysis of climate hazards and their impacts done in Chapter 4. Then, step 3 is based on a black and grey literature review to identify generic adaptation strategies for addressing the climate hazards at the dairy farm (i.e., water stress, floods, crop pest infestation, climate variability, cow heat stress, and cow diseases), resulting in 14 adaptation strategies. Step 4 selects suitable adaptation strategies for addressing the climate hazards present in the case studies. Finally, step 5 is about quantification to identify win-win adaptation strategies, which are selected based on the net environmental cost of an adaptation strategy. Here a win-win strategy is defined as one that outweighs its environmental cost by additional benefits.

In order to achieve these types of win-win strategies, the integration of different methodologies and tools can support the dairy industry in adapting and mitigating climate change. Given the little attention that has been paid to adaptation strategies at dairy farms compared to mitigation strategies, this chapter seeks increasing awareness and urgency of integrating climate change adaptation plans into the dairy industry's agenda, where win-win strategies are considered.

Chapter 6 implements the toolbox in a company context to disclose the biophysical impacts of climate hazards on the dairy farms of the company. Arla Foods, Denmark is the largest dairy cooperative in the world, where the dairy farms are mainly concentrated across four countries: United Kingdom, Germany, Sweden, and Denmark. The disclosure was carried out following the recommendations of the Task Force on Climate-Related Financial Disclosures

(TCFD), which is a volunteering document performed by companies that oversee the Corporate Finance Department of Arla Foods. However, one of the weaknesses of the TCFD is that it only provides a few tools, methods, or models to address climate hazards and their impacts. The toolbox developed in Chapter 4 is applied to evaluate the climate hazards on dairy farms located across these four countries. As data sources to address raw milk losses from cow heat stress and diseases are based mathematical models which require a certain expertise for their application a user-friendly application was created, so it can be used for future disclosures by that the department. The European Green Deal through a Corporate Sustainability Reporting Directive is expected to push industries in reporting the impacts that climate change poses to them. The implementation of the developed toolbox aims to support the dairy industry in providing transparent and consistent reporting as well as in adapting to the unavoidable effects of climate change.

Finally, **Chapter 7** provides a reflection on the key findings and also summarizes the conclusions of this thesis. As part of the reflection, it specifies the knowledge contribution of this thesis to European policies and guidelines that focuses on adaptation to climate change in the dairy industry. For instance, the reinforcement of the “new Strategy on Adaptation to Climate Change” from the European Commission. Also, the toolbox proposed in this thesis provides an in-depth analysis of climate hazards and their biophysical impacts, so it contributes to climate change impact assessments at dairy farms. It is expected that it is added to the list of proposed tools and methods provided by the TCFD. In this sense, it can support the dairy industry as this type of disclosure is aimed for companies. In addition, a clear understanding of climate hazards and their impacts will support the design of site-specific efficient adaptation strategies.

This thesis has been carried out within the framework of the PROTECT (Predictive mOdelling Tools to evaluate the Effects of Climate change on food safety) ITN (<http://www.protect-itn.eu/>). The motivation of this ITN was built on the emergency of looking at the challenge to maintain a balance between dairy productivity, food safety, and environmental preservation.

RESUMO

O cambio climático é xa unha realidade presente e espérase que os seus efectos globais empeoren. Para evitar o incremento de impactos irreversibles derivados do cambio climático, limitar o incremento de temperatura a 1,5 graos Celsius é o obxectivo de iniciativas globais, como o Acordo de París, e iniciativas europeas, como o *Green Deal*. Segundo este obxectivo, débense acadar emisións netas nulas de gases de efecto invernadoiro (GEI) no ano 2050.

En todo o mundo, o sector leiteiro é recoñecido como unha fonte importante de emisións de GEI, debido á gran contribución do metano emitido, e tamén responsable doutros impactos medioambientais sobre a auga e os solos. Neste contexto, o sector leiteiro europeo ten traballado dende hai anos para reducir o seu impacto medioambiental e, en liña coas iniciativas mencionadas, fixou obxectivos medioambientais ambiciosos para 2050: acadar emisións netas nulas de GEI por parte do sector mentres se promove o uso eficiente da auga e do solo.

A análise de ciclo da vida (ACV) é unha metodoloxía integral para avaliar os impactos ambientais dun produto ou proceso ao longo de todo o seu ciclo de vida, desde a extracción da materia prima ata a súa eliminación. É unha metodoloxía moi estendida que ten apoiado repetidamente ao sector leiteiro xa que proporciona unha avaliación integral dos impactos ambientais das explotacións leiteiras, permitindo o desenvolvemento de estratexias para mitigar eses impactos e examinando o seu avance no tempo.

A metodoloxía da ACV representa un apoio ao sector leiteiro na súa transición cara obxectivos ambientais ambiciosos para 2050. Non obstante, esta transición vese afectada pola evolución do clima derivada do quecemento global e os chamados riscos climáticos, que supoñen un desafío adicional á transición do sector leiteiro. Todos os escenarios climáticos utilizados para 2050 prevén riscos climáticos máis intensos, mais presentando variacións significativas entre as cinco rexións bioxeográficas presentes en Europa (nomeadamente as rexións atlánticas, de montaña, norte de Europa, continental e mediterránea). Os riscos climáticos interactúan cos ecosistemas e ameazan as cadeas de valor do leite, principalmente a produción primaria (é dicir, a produción de leite cru e o subministro de alimento para o gando), xa que esta é a etapa máis vulnerable ao cambio climático. Relacionados coa produción primaria, os riscos climáticos causan impactos biofísicos xa que teñen un efecto tanto sobre os sistemas biolóxicos (vacas leiteiras e cultivos) como físicos (auga, solo e atmosfera). Como consecuencia, estes impactos repercuten no rendemento e na seguridade alimentaria das explotacións leiteiras, modificando o impacto ambiental por unidade de leite cru producido. Cómpre definir estratexias de adaptación, adaptadas a unha granxa leiteira en particular, para reducir o impacto dos riscos climáticos tendo en conta a súa variabilidade xeográfica e os seus impactos biofísicos. Estas estratexias necesitan materiais e recursos, o que pode dar lugar a novas emisións de GEI e a un maior impacto ambiental do leite. Neste senso, é esencial avaliar de forma meticulosa tanto os beneficios coma os custos ambientais e analizar as posibles disxuntivas entre ambos. O deseño de estratexias de adaptación debe procurar tanto a supervivencia do sector leiteiro fronte ao cambio climático como unha redución do impacto ambiental que permita atinxir os obxectivos medioambientais 2050.

Hai un gran número de riscos climáticos e incerteza derivada de factores non- climáticos (por exemplo, melloras tecnolóxicas, cambios de mercado e de regulación), que interactúan entre si, afectando aos elementos do inventario do ciclo de vida (ICV). Construír un ICV que teña en conta os efectos futuros do cambio climático é unha tarefa complexa xa que son necesarias diferentes fontes de datos (é dicir, modelos de simulación, ferramentas, software e revisións da literatura científica) con diferentes requisitos de habilidades computacionais para cuantificar os cambios no ICV. Ademais, a complexidade está asociada á incerteza inherente aos datos e modelos climáticos empregados.

Esta tese esta composta de 7 capítulos descritos brevemente a continuación:

O **Capítulo 1** serve de introdución ofrecendo unha comprensión clara da interacción entre os efectos do cambio climático ao longo das cadeas de valor dos produtos leiteiros e os seus impactos ambientais. Identificáronse cualitativamente as conexións entre os riscos climáticos, os seus impactos biofísicos e o seu efecto sobre o desempeño ambiental das cadeas de valor lácteas, formando unha matriz que relaciona o conxunto destes elementos. Como resultado, identificáronse sete riscos climáticos como os máis relevantes: estrés hídrico, asolagamentos, infestación de pragas de cultivos, variabilidade climática, estrés por calor do gando, enfermidades do gando e riscos para a seguridade do leite. Obsérvase que o estrés hídrico pode modificar a dispoñibilidade de augas subterráneas e superficiais, levando a unha posible variación nas emisións de GEI debido ao uso de auga de fontes non renovables. Os asolagamentos, tanto permanentes como súbitos, xunto con moitos outros factores climáticos (estrés hídrico, variabilidade climática e infestación de pragas dos cultivos) e factores non climáticos, provocan cambios na distribución xeográfica dos cultivos. A infestación de pragas de cultivos levará previsiblemente a un uso adicional de pesticidas por parte dos agricultores como medida para facer fronte ao aumento de pragas. A variabilidade climática é outro risco climático analizado nesta etapa que provoca cambios no rendemento dos cultivos, ben de xeito positivo ou negativo, así como cambios na distribución xeográfica dos cultivos. O estrés por calor das vacas é un risco climático que leva a unha redución da produción de leite, que se pode cuantificar en perdas de leite cru. Para aliviar o estrés térmico das vacas, cómpren sistemas de redución da calor; non obstante, precisan de enerxía e auga, o que supón un aumento das emisións de GEI e do uso da auga na explotación leiteira. Finalmente, a enfermidade das vacas é un risco climático que tamén está ligado ás perdas de leite cru. A mamite bovina considérase a enfermidade máis común en explotacións leiteiras a nivel mundial. Altera a calidade do leite cru, pode estar asociada a riscos de seguridade alimentaria e reduce a produción de leite de vaca, o que tamén se traduce en perdas adicionais de leite cru. Revisando o resto das etapas do ciclo de vida (é dicir, fábrica de produtos leiteiros, distribución, venda e consumo), os riscos climáticos identificados aquí tamén están relacionados coa seguridade alimentaria. Como consecuencia do cambio climático, as temperaturas máis altas e os cambios nas precipitacións están asociados á presenza de riscos relacionados cos alimentos (é dicir, riscos biolóxicos e químicos), que afectan á seguridade dos produtos leiteiros, que están directamente ligados a posibles perdas e desperdicios de alimentos. A partir desta análise cualitativa, conclúese que os riscos climáticos e os seus impactos biofísicos afectan con certeza ao desempeño ambiental do sector leiteiro. O seguinte chanzo é a cuantificación e relación entre os riscos, impactos e resultados ambientais.

O **Capítulo 2** ofrece unha visión xeral dos métodos empregados nesta tese para estimar os cambios no desempeño ambiental do sector leiteiro baixo os efectos futuros do cambio climático.

O capítulo divídese en tres seccións. En cada sección descríbense por separado a ACV, a avaliación de riscos (RA polo seu acrónimo común en inglés) e as táboas *Input-Output* (IO) e despois como se combinaron entre si para acadar o obxectivo desta investigación. Os métodos céntranse na etapa de produción primaria (a explotación de produtos leiteiros e a produción de cultivos), a principal contribuínte ao cambio climático e tamén a máis vulnerable ao quecemento global segundo os resultados do capítulo 1. A integración das tres ferramentas dan como resultado un enfoque prometedor para garantir a seguridade alimentaria e os obxectivos ambientais para 2050.

A ACV é unha metodoloxía ben establecida para estimar o impacto ambiental das explotacións leiteiras. Non obstante, a estimación dos desproveitos de alimentos non foi tido en conta, ou polo menos non co nivel de detalle requirido no ICV, o que pode resultar nunha valoración defectuosa do impacto ambiental do leite producido. A integración da RA na ACV proporciona unha estimación transparente e detallada do leite perdido nas explotacións leiteiras, á vez que distingue entre rexións que poden verse afectadas de forma diferente polo cambio climático. O obxectivo desta integración é o de examinar se garantir a seguridade alimentaria leva a un maior impacto ambiental e viceversa. A integración pode detectar e evitar compensacións cando se busca reducir os riscos de seguridade alimentaria e as perdas e o desperdicio de alimentos ao tempo que se reduce a contribución ao cambio climático e outros impactos ambientais nas cadeas de valor dos produtos leiteiros.

En moitas ocasións non se dispón de información como a orixe alimento do gando vacún procedente de fóra da explotación leiteira. Porén, é necesaria unha análise detallada xa que a alimentación das vacas é un dos principais contribuíntes ao impacto ambiental no ciclo de vida. O uso de táboas IO, como FABIO (*Food and Agriculture Biomass Input-Output*), permite rastrexar a orixe dos cultivos e, a continuación, obter información específica dependendo da orixe como os seus rendementos, que se espera, evolucionen de forma desigual en todo o mundo.

O **Capítulo 3** céntrase en estimar as perdas actuais e futuras de leite cru causadas pola mamite bovina en tres rexións bioxeográficas de Europa e os escenarios climáticos para 2050 mediante a implementación da RA. A porcentaxe estimada de perdas anuais de leite cru incorpórase despois a un ICV teórico construído no capítulo 4 para estimar o custo ambiental do leite cru perdido debido á mamite. Este capítulo ofrece un exemplo ilustrativo de como avaliar o impacto do cambio climático na saúde das vacas e, en definitiva, na cadea de valor do leite. A mamite bovina é considerada a enfermidade máis común presente nas granxas de leite de todo o mundo. A mamite é inducida por varios microorganismos patóxenos que entran na glándula da vaca a través da canle do teto, tanto de forma contaxiosa como ambiental. Un dos patóxenos máis comúns illados nas explotacións leiteiras europeas é o *Staphylococcus aureus*. A mamite bovina aumenta as perdas de leite cru, que se producen de dúas formas nas explotacións leiteiras. As perdas indirectas de leite cru representan o leite que non se pode producir como resposta á diminución do rendimento de leite de vaca debido á infección. As perdas directas de leite cru inclúen o leite que se descarta xa que non cumpre os requisitos de calidade do leite cru en termos de reconto de células somáticas.

Desenvolveuse un modelo de avaliación da exposición e un modelo probabilístico para predicir potenciais perdas de leite cru vencelladas a unha redución do rendimento de leite e á vulneración dos límites de *S. aureus* e células somáticas no leite. O modelo inclúe as temperaturas actuais e proxectadas para 2050 segundo os *Representative Concentration Pathways* (RCP) do IPCC, dos que seleccionaron o RCP2.6 como escenario optimista con

grandes logros de mitigación, o RCP4.5 como escenario intermedio, e o RCP8.5 como un escenario pesimista onde non se realizan esforzos para reducir as emisións de GEI. Ademais dos parámetros climáticos, tamén se contemplaron prácticas de mellora, como o aumento da produción de leite por vaca grazas a razas máis produtivas e a redución da prevalencia de mamite pola dispoñibilidade de tratamentos futuros máis eficaces. O modelo mostrou que entre as tres rexións (é dicir, atlántica, mediterránea e continental), as perdas de leite cru oscilaban entre o 1,06% e o 2,15%. Non obstante, aumentaron ata un 3,21% nos escenarios de cambio climático cando non se consideraban melloras na explotación. En canto á variación xeográfica, as perdas potenciais de leite máis altas rexistráronse para o Mediterráneo e as máis baixas para a rexión continental. En canto ao cumprimento dos límites regulamentarios, a media dos niveis de *S. aureus* e o recuento de células somáticas no leite non os superou en ningunha rexión ou escenario. Nos extremos da distribución, con todo, o percentil dez permaneceu por riba dos límites de *S. aureus* no casos de estudo atlántico e mediterráneo. Ademais, demostrouse que as melloras nas explotacións teñen un efecto significativo sobre as perdas de leite cru.

En canto á validación do modelo, comparáronse as perdas de leite previstas cos valores aparecidos na literatura, estando os valores estimados dentro do intervalo dos valores da literatura. Desafortunadamente, esta validación só foi posible para o escenario de referencia xa que non hai proxeccións de perdas de leite cru a nivel de explotación para 2050.

O Capítulo 4 propón un conxunto de ferramentas (*toolbox*) para estimar os cambios no ICV debido aos impactos biofísicos dos riscos climáticos nas explotacións leiteiras e os seus impactos ambientais en diferentes horizontes xeográficos e temporais. Os riscos climáticos e os seus impactos biofísicos abordados son os seis riscos identificados anteriormente no capítulo 1. A *toolbox* componse de tres módulos nos que se empregaron diferentes fontes de datos (modelos de simulación, ferramentas, software e literatura) para xerar a información necesaria para abordar os riscos climáticos (é dicir, estrés hídrico, asolagamentos, infestación de pragas de cultivos, variabilidade do clima, estrés por calor das vacas e enfermidades das vacas) e os seus impactos biofísicos presentes nas explotacións leiteiras.

O primeiro módulo define o contexto xeográfico e climático das rexións de estudo. O segundo módulo estima a intensidade dos riscos climáticos e os seus impactos biofísicos para 2050 nas explotacións leiteiras. O terceiro módulo recolle os cambios porcentuais cuantificados no inventario causados polo cambio climático co obxectivo de construír o ICV teórico do escenario futuro (neste caso 2050). Despois, é posible pasar á fase de análise do ICV e realizar unha análise de contribución para identificar os riscos climáticos máis significativos. Aquí tamén se incorpora a estimación das perdas anuais de leite cru do capítulo 3 na construción do ICV teórico onde leva a cambios dos fluxos de referencia. Esta caixa de ferramentas está destinada a ser integrada na fase de ICV do ACV, xa que xera ICV teóricos que dan conta dos impactos biofísicos dos riscos climáticos.

Dado que os impactos do cambio climático son escenarios xeográficos e climáticos desiguais, as fontes de datos seleccionadas deben cumprir dous criterios: i) cubrir diferentes localizacións xeográficas e ii) abranguer diferentes ventás de tempo en varios escenarios climáticos. Cando non se atoparon este tipo de datos, houbo que xeralos, ben xuntando modelos existentes ou ben desenvolvéndoos especificamente para a explotación leiteira obxecto de estudo. Por exemplo, utilizáronse fontes de datos dispoñibles para xerar información sobre os seguintes riscos climáticos e os seus impactos biofísicos: estrés hídrico, asolagamentos, infestación de pragas de cultivos e variabilidade climática. Non obstante, non había datos dispoñibles para abordar o estrés por calor das vacas e as enfermidades en diferentes rexións,

ventás temporais e escenarios climáticos. Este tipo de datos xeráronse ampliando neste traballo os modelos dispoñibles.

A caixa de ferramentas foi probada en dous casos prácticos para demostrar a súa aplicabilidade. Os dous casos prácticos corresponden con dúas rexións con condicións climáticas distintas no escenario SSP2-4.5: explotacións leiteiras españolas na rexión mediterránea de Europa e granxas leiteiras suecas no norte de Europa. Como resultado da implementación da caixa de ferramentas, estimáronse as perdas de leite cru causadas polo estrés por calor das vacas e as enfermidades das vacas como responsables do aumento do potencial de quecemento global e do esgotamento da auga, mentres que a infestación de pragas dos cultivos e a variabilidade climática son as responsables do aumento da ocupación da terra. Ao integrar modelos xa dispoñibles e adaptados, con diferentes niveis de complexidade e requisitos computacionais, a caixa de ferramentas desenvolvida permite explorar os posibles escenarios aos que se enfrontarán as explotacións leiteiras europeas e comprender como lles afectará o cambio climático e o seu rendemento ambiental.

O **Capítulo 5** identifica as estratexias de adaptación específicas para un lugar e avalía o seu custo ambiental neto para identificar estratexias de ganancia mutua (*win-win*), definidas como aquelas que permiten adaptarse ao cambio climático a un custo ambiental máis baixo ao tempo que garanten a produción de granxas de leite e a seguridade alimentaria. Para iso propónse un marco de cinco etapas. No primeiro paso defínense os horizontes temporais-climáticos e xeográficos. En consonancia co capítulo 4, defínense dúas explotacións leiteiras situadas nas rexións do Mediterráneo e do norte de Europa no escenario SSP2-4.5. No segundo paso, identifícanse os riscos climáticos específicos do sitio e os seus impactos biofísicos relacionados. Este paso baséase na análise en profundidade dos riscos climáticos e os seus impactos realizada no capítulo 4. A continuación, o paso 3 baséase nunha revisión da literatura, tanto científica como técnica, para identificar estratexias xenéricas de adaptación que aborden os riscos climáticos na explotación leiteira dando como resultado 14 estratexias de adaptación. O paso 4 selecciona estratexias de adaptación adecuadas para abordar os riscos climáticos específicos. Finalmente, o paso 5 trata sobre a cuantificación para identificar estratexias de adaptación de ganancia mutua, que se seleccionan en función do custo ambiental neto dunha estratexia de adaptación. Aquí defínese unha estratexia de ganancia mutua como aquela que supera o seu custo ambiental mediante beneficios adicionais.

Para conseguir este tipo de estratexias de ganancia mutua, a integración de diferentes metodoloxías e ferramentas pode apoiar á industria láctea na adaptación e mitigación do cambio climático. Dada a pouca atención que se lle prestou ás estratexias de adaptación nas explotacións leiteiras en comparación coas estratexias de mitigación, este capítulo busca aumentar a concienciación e a urxencia de integrar os plans de adaptación ao cambio climático na axenda da industria leiteira.

O **Capítulo 6** aplica a caixa de ferramentas nun contexto empresarial para dar a coñecer os impactos biofísicos dos riscos climáticos nas explotacións leiteiras dunha empresa. A empresa en cuestión, Arla Foods, con sede en Dinamarca é a maior cooperativa de produtos leiteiros do mundo, onde as granxas de leite se concentran principalmente en catro países: Reino Unido, Alemaña, Suecia e Dinamarca. A declaración dos datos e prácticas empresariais levouse a cabo seguindo as recomendacións do *Task Force on Climate-Related Financial Disclosures* (TCFD), un documento voluntario. Non obstante, unha das debilidades do TCFD é que só proporciona algunhas ferramentas, métodos ou modelos para abordar os riscos climáticos e os seus impactos. Así, a caixa de ferramentas desenvolvida no capítulo 4 aplícase para avaliar os riscos climáticos

nas explotacións leiteiras situadas nestes catro países. Por exemplo, as fontes de datos para abordar as perdas de leite cru derivadas do estrés por calor das vacas e as enfermidades precisan de modelos matemáticos complexos. Para a súa aplicación sinxela, creouse unha aplicación accesible e fácil de usar, polo que pode ser utilizada no futuro en Arla Foods. É probable que o *Green Deal*, mediante unha Directiva de Informes de Sostibilidade Corporativa impulse ás industrias a informar dos impactos que lles supón o cambio climático. Así, a aplicación da caixa de ferramentas desenvolvida ten como obxectivo apoiar a industria leiteira para proporcionar informes transparentes e coherentes, así como para adaptarse aos efectos inevitables do cambio climático.

Por último, o **Capítulo 7** ofrece unha reflexión sobre as principais conclusións desta tese. Como parte da reflexión, concreta a achega de coñecemento desta tese ás políticas e directrices europeas que se centran na adaptación ao cambio climático na industria láctea. Por exemplo, o reforzo da "*nova Estratexia de Adaptación ao Cambio Climático*" da Comisión Europea. Así mesmo, a caixa de ferramentas proposta nesta tese proporciona unha análise en profundidade dos riscos climáticos e dos seus impactos biofísicos, polo que contribúe ás avaliacións de impacto do cambio climático nas explotacións leiteiras. Espérase que se engada á lista de ferramentas e métodos propostos proporcionada polo TCFD xa que pode apoiar á industria láctea neste tipo de comunicacións especificamente dirixida ás empresas. Ademais, unha comprensión clara dos riscos climáticos e dos seus impactos apoiará o deseño de estratexias de adaptación eficientes específicas para cada lugar.

Esta tese realizouse no marco da *initial training network* (ITN) PROTECT (Predictive modeling Tools to evaluate the Effects of Climate change on food safety, <http://www.protect-itn.eu>). A motivación desta ITN construíuse sobre a emerxencia de manter un equilibrio entre a produción de alimentos, a seguridade alimentaria e a preservación do medio ambiente.

1. INTRODUCTION

SUMMARY

This chapter describes the context in which the thesis is developed as well as it describes its objectives and structure.

There is a clear interaction between climate change and the environmental impact of the dairy sector, and thus, this chapter provides clear understanding on it. But before that, the environmental impact of the dairy sector is narrowed down from a global to European perspective. Then, the effects of climate change on the dairy sector are described as they will represent a challenge for this sector. However, these effects will not remain uniform across regions and climate change scenarios, and thus, geographical regions and available scenarios are described to define the spatiotemporal context of this thesis. Finally, climate related hazards will not be the only challenge that the dairy sector will tackle, but also non-climate-related hazards (e.g., regulatory transition) and they are also mentioned here.

Part of this chapter is built on the following open access scientific paper:

- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2021). Analysing the interaction between the dairy sector and climate change from a life cycle perspective: A review. *Trends in Food Science and Technology*, 126(168–179) <https://doi.org/10.1016/j.tifs.2021.09.001>

1.1 EUROPEAN DAIRY SECTOR

Climate change is one of the major challenges the world is facing today. Limiting global warming to 1.5 degrees Celsius implies achieving net zero greenhouse gas (GHG) emissions globally by 2050, along with a significant reduction in non-CO₂ GHG, primarily methane (CH₄) (IPCC, 2022). The dairy sector has been recognized for being a significant contributor to climate change (FAO and GDP, 2018). In 2015, this sector emitted 1.7 million tonnes of CO₂e, which represents around 3.4% of the total related anthropogenic CO₂e¹ emissions (Olivier, Janssens-Maenhout, Muntean & Peters, 2016) and an increase of 18% compared to 2005, mainly due to higher consumer demand. During the same period, the emission intensities per kilogram of milk were reduced by 11% thanks to production efficiency improvements. Without them, the emissions from this sector would have increased by up to 38% (FAO & GDP, 2018). Among the different GHGs involved, methane (CH₄) is the main one representing up to 63.3% of the total carbon footprint of an average dairy product, followed by nitrous oxide (N₂O, up to 24.5%) and carbon dioxide (CO₂, up to 12.2%) (FAO & GDP, 2018). Besides, global warming, water use and water eutrophication have also been reported as relevant environmental impacts along the dairy value chains (FAO & GDP, 2018; Gerber, Vellinga, Opio, Henderson & Steinfeld, 2010). To analyse the contribution to climate change and other environmental impacts of raw milk and dairy products, 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 quantified and translated into environmental impact categories. LCA has been extensively applied to a large number of dairy products. See for example Djekic et al. (2014), Üçtuğ (2019) and Yan et al. (2011). The Environmental Product Declarations (EPD, 2021) and related Product Category Rules (PCR) have been developed for underlying and setting standards towards environmental impact assessments specifically for dairy products (such as raw milk² and processed milk³). Individual environmental indicators, such as Carbon Footprint (CF), which quantifies the GHG emissions of products along their 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 et al., 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).

Moving from a global to a European context, efforts to reduce the environmental impact of raw milk and dairy products have also been part of the agenda of the European dairy sector. The implementation of climate change mitigation strategies, optimization of the entire production line, and improvements of dairy farm practices with special focus on reducing enteric fermentation (e.g., more digestible and better feed quality, additive utilization and genetics) are examples of these efforts (EDA, 2019; FAO and GDP, 2018; Gerber et al., 2013). At present, the carbon footprint of a kg of fat-protein-corrected milk (FPCM) is 0.9 – 1.5 kgCO₂e at an average production system across Europe (Mazzetto et al., 2021)⁴. Among the stages that compound the dairy products value chains, the dairy farm is the largest contributor to global warming since it accounts for roughly 80% of the total carbon footprint of dairy products, being CH₄ emissions from enteric fermentation the main source (up to 58.5% of the

¹ Carbon oxide equivalent (CO₂e) is a standard unit to compare the radiative forcing of different GHGs to that of CO₂ and it is used to express the carbon footprint of a product or service (ISO 14064-1, 2018).

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

³ PCR 2013:17 available at <https://test1.environdec.com/PCR/Detail/?Pcr=9261>, expired in 2021/09/01

⁴ The studies included in Mazzetto et al. (2021) do not consider land use change.

carbon footprint of raw milk). To a lesser extent, N₂O emissions from fertilizers for the on-farm feed production (i.e., roughage) and off-farm feed production (i.e., concentrated feed) contribute to 20%. Then, N₂O and CH₄ emissions from manure management signify 9.3%, whereas CO₂ emissions from the use of energy at the barn and from feed production represent 12.2% of the total carbon footprint (FAO and GDP, 2018). The Product Environmental Footprint (European Commission, 2012) and related Product Environmental Footprint Category Rules for dairy products⁵ were developed at an European context. Similarly, this aid to assure a harmonized environmental performance evaluation to ensure comparison and facilitate the communication of results of LCA studies.

To align to climate actions, such as the Paris Agreement commitment (UNFCCC, 2016), European Green Deal initiative (EC, 2021a), and the Farm to Fork strategy (EC, 2021), the European dairy sector has the compromise to become climate neutral (i.e., net-zero GHG emissions) by 2050 (EDA, 2019). Nevertheless, the European dairy sector will encounter climate change-related challenges by 2050 that might confront this compromise. 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, 2014a). Some of these climate hazards 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 et al., 2017) and their technical efficiency and environmental performance might be compromised (Key & Sneeringer, 2014). Several qualitative climate change impact assessments (CCIA) have been carried out in which they project, analyse and diagnose the impacts of climate change and emerging risks on agricultural systems including the dairy sector (Hristov et al., 2020). Guidelines from different institutions have been proposed to perform CCIA across different geographical areas and sectors such as ClimateADAPT (2023), IPCC (1994) and The World Bank (2019). Within the dairy products value chains, the primary production stage is the most vulnerable to the effects of climate change since crop production and raw milk production are agricultural systems that are very sensitive to climatic variations, which are expected by climate change. Extreme weather events are likely to occur more frequently and represent a challenge to the productivity of the crops used for animal feeding, 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 in temperature, cows' performance and health might be influenced, having negative repercussions on their milk production (Fodor et al., 2018). It is known that the proliferation of vector-borne diseases that include foodborne pathogens is expected to benefit from the changes in climatic conditions caused by climate change (EFSA, 2020). Therefore, an increase in the microbial load increases the risk of contamination of raw milk and also dairy products (Misiou & Koutsoumanis, 2021). As a result, higher quantities of raw milk and dairy products might not comply with food safety standards, leading to food losses and waste (FLW). In particular, the rise of average global temperatures, the increased occurrences of rain events and the modification of relative humidity are expected to increase the prevalence of bovine mastitis and, consequently, contribute to cow discomfort and heat stress (Hempel et al., 2019). Raw milk losses mean resources used and emissions generated for nothing, increasing the environmental impact of a unit of dairy product consumed (UNEP, 2021).

1.2 DAIRY SECTOR AND CLIMATE CHANGE INTERACTION

It is clear that there is an interaction between the dairy sector and climate change (Figure 1.1). On one direction, the dairy sector significantly contributes to climate change, besides impacting other environmental categories; while, on the other, the effects of climate change influence the performance of the dairy products value, and the associated environmental burdens. Moreover, the potential measures to confront climate hazards and their biophysical impacts on the dairy sector are expected to have environmental consequences, leading to a contribution to climate change and creating an aggravating nexus.

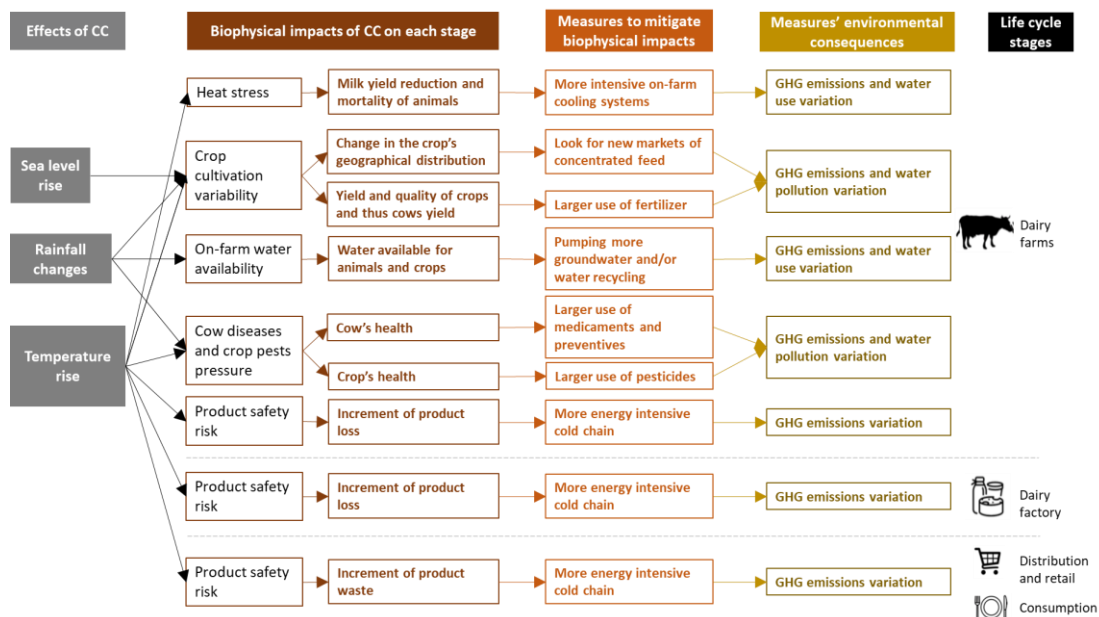


Figure 1.1. Main interactions of climate hazards and their biophysical impacts on the environmental performance of the dairy value chains.

The temperature rise was found as the most substantial effect of climate change as it affects more elements along 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 is the provision of shaded areas (EEA, 2017), while in confined systems, the use of cooling systems and/or water sprinklers 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. For instance:

- 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).
- 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, the genetic selection of dairy cows' more resistance to heat stress has been identified as a promising strategy to adapt to the extreme temperatures caused by climate change (EEA, 2017; Misiou & Koutsoumanis, 2021). In 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). Milk yield of dairy cows without this gene tends to decrease during summer season but keep constant in cows with this gene (Dikmen et al., 2014; Hansen, 2020). A dairy herd more resistant to heat stress can result in less time of use of the on-farm cooling systems, and thus, affecting the environmental performance of the dairy farm. There have also been efforts to continuously improve the cows' milk production by increasing their peak yield so an earlier lactation is reached, and it is possible through feeding strategies and genetic improvement (Bórawski et al., 2020). However, these improvements are likely to be outweighed in regions with a higher risk of heat stress.

Temperature rise together with heavy rainfall events are expected to benefit the geographic expansion of pathogens and increase the 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 (Rojas-Downing et al., 2017). 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). Besides, the use of antimicrobials entails an environmental cost not only due to the production of the drugs themselves but also related to the animal excretion and milk losses, which represent the major impact in both environmental and economic terms (Noyes et al., 2021). 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).

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, 2014a). 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, 2014b). 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) (EEA, 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 et al., 2014). In past years, scientific research has been carried out to improve crop yield (Dhankher & Foyer, 2018), 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 (Dijkman et al., 2018).

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 rise in coastal regions can aggravate the situation, provoking seawater intrusion in coastal aquifers and wells (Colombani et al., 2016). Pumping more groundwater and/or recycling water to supply animals and crops are measures identified (Ciscar et al., 2018), and following the so-called water-energy nexus, energy is required to supply freshwater to animals and water is needed to produce that required energy (Olsson, 2015). On-farm water supply also influences the on-farm electricity consumption, which 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 Figure 1.1. 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 FLW. Many initiatives and strategies have been launched to fight food losses and waste 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 et al., 2018). At the dairy factory stage, more energy-intensive 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 et al., 2021). The dairy sector 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 to assess the contribution to climate change of any corrective measure is expected. However, a detailed and comprehensive assessment on how the effects of climate change will affect the European dairy sector and its environmental performance has not yet been covered as done in this research. There might not be certainty on the level of the climate hazards and their biophysical impacts on the dairy sector, but there is a certainty that they will occur and threaten the dairy sector unevenly depending on its geographic location and climate scenario.

1.2.1. Geographical regions

Climate change is a global phenomenon that cause a diverse array of climate hazards across the planet and can pose a risk to the various human-relevant sectors, such as agriculture. They

include an increase in average temperature that leads to ice caps melting, and consequently, sea level rise. Loss of biodiversity is also a consequence of this global issue, which can have detrimental effects on the health and productivity of the ecosystems. Changes in average temperatures, along with longer periods of drought and altered precipitation patterns, may diminish crop yields and cause food shortages in certain regions of the world (IPCC, 2022). Whereas some regions may experience more frequent and severe climate hazards, others may be less affected. According to the EEA (2017a), the occurrence of climate hazards will differ throughout Europe's biogeographical regions, which are characterized based on how climate change will affect them and their vulnerabilities will manifest (Figure 1.2):

- The **Mediterranean** region, which encompasses the southern parts of Europe, is the most vulnerable one. The impacts of climate change are likely to be significant in the Mediterranean. The region is already vulnerable to extreme weather events, heatwaves, droughts, and wildfires, and they are expected to be intensified in the future. All of this can have significant impacts on water resources and the availability of freshwater for agriculture, industry, and domestic use. In addition, disease vectors are forecasted climatic hazards for this region that will have biophysical effects on agricultural systems (EEA, 2017, 2019).
- The **Atlantic** region, which includes western Europe, is anticipated to experience an increase in heavy precipitation occurrences. In addition, this region will be the most impacted by sea level rise, which will result in coastal flooding. River flooding and excessive precipitation, especially during the winter, will be among the threats to be anticipated in this region (EEA, 2017, 2019).
- The **Continental** region encompasses the eastern and central region of Europe. This region is anticipated to experience an increase in average temperatures, as well as more frequent and severe heatwaves and summer droughts. This region may also be affected by an increase in the risk of flooding due to strong rains and rivers (EEA, 2017, 2019).
- The **Mountain** regions encompass all mountainous regions of Europe. In these places, the average temperature will rise faster than other regions. Due to the melting of ice layers and the shrinking of glaciers, it is anticipated that plant and animal species will ascend. However, this will increase the likelihood of rockfalls and landslides in certain places (EEA, 2017, 2019).
- The **Northern** region of Europe is prone to heavy precipitation events and flooding events. Additionally, agricultural yield and farmland are anticipated to rise as a result of improved temperature conditions and a decline in lake and river ice cover (EEA, 2017, 2019).

According to the most recent figures (Eurostat, 2022), 10 countries were responsible for 85% of the total raw milk production in Europe in 2020 (Figure 1.2). Along these countries, four biogeographical regions are identified, which are Atlantic, Mediterranean, Continental, and Northern, leaving aside the mountain region.

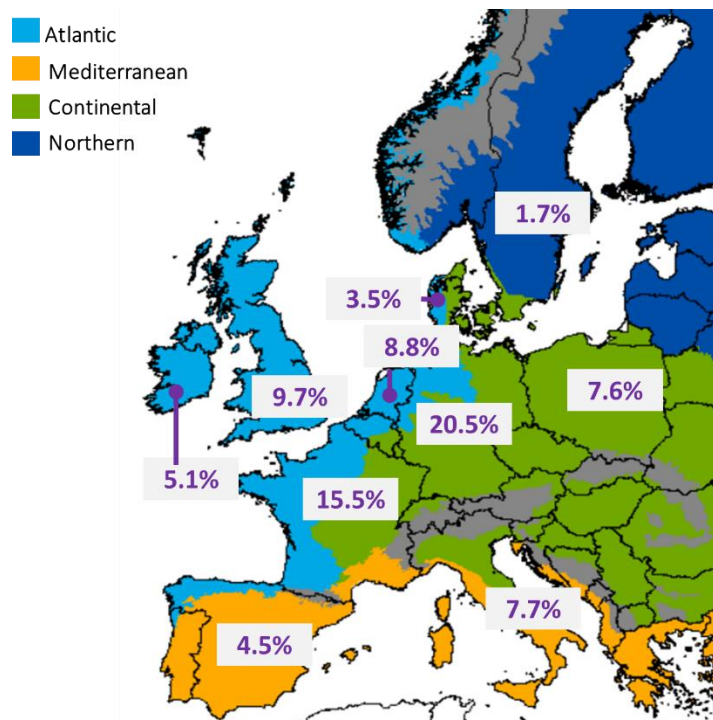


Figure 1.2. Biogeographical regions present across the 10 largest dairy producers in Europe. Percentages represents the contribution of raw milk production per country.

1.2.2. Climate scenarios

The intensity of climate hazards and their biophysical impacts will also vary based on the climate scenario by 2050. Future projections on global warming are driven by emissions and concentrations from the Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) scenarios. The SSPs have been developed as a set of scenarios to describe the different development paths of the global society over this century (O'Neill et al., 2017):

- SSP1 refers to a sustainable and fully “green” (i.e., low emissions) world in which swift and coordinated actions is made to reduce GHG emissions.
- SSP2 is seen as the “middle of the road” world, where tendencies largely adhere to the historical patterns and some efforts are made to establish a more sustainable economy.
- SSP3 shows a future with high emissions and few efforts to reduce GHG emissions.
- SSP4 is a scenario that likewise reflects a high-emissions society, but where economic and population rates are significantly higher than in SSP3.
- SSP5 is a business-as-usual (BAU) world characterized by rapid and unrestricted economic and energy consumption growth.

SSPs are combined with the Representative Concentration Pathways (RCPs) were developed as part of the IPCC’s Fifth Assessment Report (AR5) and periodically revised (IPCC, 2022). As a result of the socioeconomic developments (i.e., SSPs), a range of probable radiative forcing levels and GHG concentrations in the atmosphere are considered in the RCPs. They are derived from global climate models, ranging in different temperature outcomes depending on the temporal horizon:

- **RCP2.6:** A "low stabilization" pathway in which GHG concentrations are stabilized at a relatively low level, leading to a minor increase in global mean temperature. This

scenario is based on robust and early mitigation efforts, such as the widespread deployment of renewable energy and energy efficiency measures, as well as CO₂ removal and carbon capture storage technologies.

- **RCP4.5:** A "medium stabilization" approach in which GHG concentrations are stabilized at a moderate level, leading in a modest increase in global mean temperature. This scenario is based on moderate mitigation efforts, although at a slower rate than RCP2.6 and is acknowledged as a plausible scenario.
- **RCP7.0:** A "medium-high stabilization" pathway in which GHG concentrations are stabilized at a higher level, leading to a reasonably large increase in global mean temperature. This scenario is predicted on limited mitigation efforts at a slower rate than RCP4.5.
- **RCP8.5:** A "high stability" pathway in which GHG concentrations continue to rise throughout the 21st century, leading to a significant increase in global mean temperature. This scenario assumes few or no mitigation efforts and a continuation of current trends in energy consumption and GHG trends.

In the Sixth Assessment Report (AR6) (i.e., most recent one) from the IPCC (2022), SSPs and RCPs are merged to generate a set of scenarios that are used to examine the likely future evolution of GHG concentrations as well as societal and environmental circumstances. The RCPs offer different assumptions regarding the trajectory of GHG emissions over the coming decades, while the SSPs indicate different assumptions regarding the trajectory of global development. By merging them, the IPCC can examine a variety of potential future climate outcomes depending on various combinations of GHG emission pathways and growth trajectories (Figure 1.3):

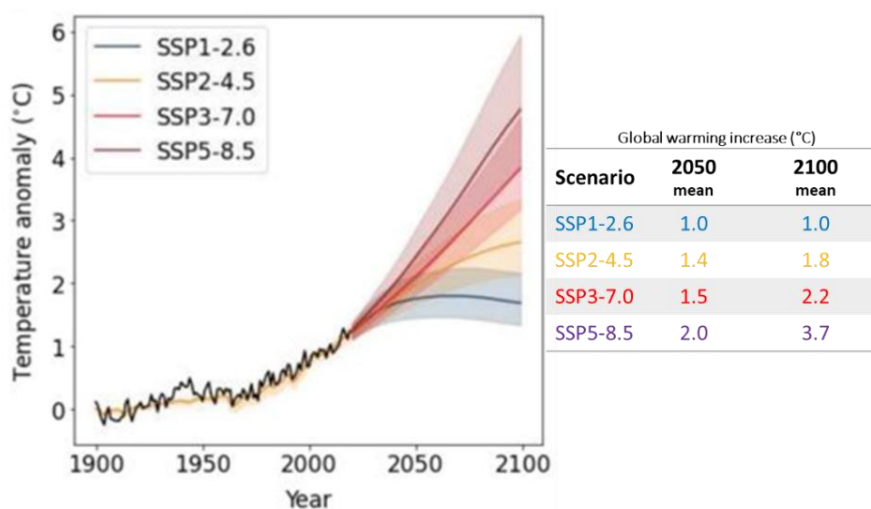


Figure 1.3. SSP-RCPs scenarios according to the AR6 report from the IPCC (IPCC, 2022; O'Neill et al., 2017).

Among the four scenarios, the SSP2-4.5 and SSP5-8.5 are the climate scenarios selected in this thesis, primarily due to data availability. The utilized data sources in this research commonly reported only on these two scenarios without focusing on the other two (i.e., SSP1-2.6 and SSP3-7.0).

The challenges of the European dairy sector by 2050 will not only be restricted to only climate-related hazards, but also all those non-climate hazards that the regulatory transition to mitigate climate change (i.e., Paris Agreement, Green Deal and Global Methane Pledge⁶) is expected to bring. For instance, to mitigate the effects of climate change and support the transition to a low-carbon economy, the global energy sector is shifting from fossil-based sources of energy production to renewable and more sustainable energy sources. It includes changes in energy infrastructure, the deployment of new technologies, and the implementation of policies that support the adoption of this type of energy sources for electricity generation in the different economic sector of the humanity (e.g., food, transport, agriculture...) (IEA, 2021).

In addition, climate policies to constrain and limit emission-intensive activities is another non-climate hazard to be considered in this thesis as they can affect the dairy industry, mainly dairy farmers. Climate policies to reduce GHG emissions from the dairy industry have been taken in place already at a European and country scale. And in some countries, these policies have been shown to be stricter than in others. This type of policies includes the introduction or hardening of climate taxes for agri-emissions. For instance, in order to reduce GHG emissions from the livestock sector in general, Denmark aims to cut its production, including the dairy production, by the introduction of taxes. Dairy farmers might shift to another economic activities as the introduction of this scheme might convert dairy production unprofitable⁷. Another example to reduce GHG emissions from the agricultural sector is in the Dutch government, which is planning to curb the number of cows and thousands of Dutch dairy farms are expected to close⁸.

Another non-climate hazard that can represent a challenge for the dairy industry by 2050 is the increasing demand for dairy products. Dairy products have been part of the human diet as they are an important source of protein and essential minerals and vitamins. The average consumption of milk and dairy products per capita in Europe was 27 kg/year by 2020 (OECD/FAO, 2020), but this demand is expected to double by 2050. Changes in dietary patterns, increment of the global population, which is projected to reach 9.8 billion people by 2050 (Gerber et al., 2013), and the income growth of developing countries will be the responsible of this increase of dairy products demand by mid-century (Alexandratos, 2012).

1.3 THESIS STRUCTURE

This research has been carried out within the framework of the Innovative Training Network (ITN) PROTECT consortium (Predictive mOdelling Tools to evaluate the Effects of Climate change on food safety) that is funded under the EU's Horizon 2020 research and innovation program. It implements predictive modelling tools to evaluate the climate change effects on the dairy sector from different perspectives corresponding to its work packages. This research falls into work package number 5, which looks at the food chain environmental sustainability in a climate change context. The naturality of ITNs seeks at provide high-level training to early-stage researchers throughout hand-on research secondments amongst the academic and industrial partners of the consortium. In particular, the present thesis was built on the work

⁶ It has been launched in 2021 to stimulate efforts for reducing global methane emissions (Global Methane Pledge, 2021).

⁷<https://www.euronews.com/green/2023/02/21/tax-on-farming-emissions-vital-to-denmarks-climate-targets-says-government-adviser>

⁸ <https://www.bbc.com/news/world-europe-62335287>

carried out at the University of Santiago de Compostela, University College Dublin in Ireland during an academic secondment and Arla Foods in Denmark during an industrial secondment.

In an era of climate change by 2050, the dairy sector has to cope with the unavoidable impacts of climate change and meet the increasing demand of dairy products while aligning with the regulation transition and keep reducing its contribution to climate change and other environmental impacts. It is evident that the dairy sector will face challenges by 2050 and its efforts to continue reducing its environmental impact might be compromised. However, the estimation of the modification of the dairy sector's environmental impact is quite complex due to the significant number of climate hazards involved and interconnected, the presence of non-climate hazards involved (e.g., technological improvements, market shifts, regulation transition), the high degree of uncertainty present in the available information on climate hazards and their biophysical impacts, and a level of expertise in the different computer languages to manipulate the available information. Even though this complex and uncertain landscape, this thesis has as a general objective to provide the appropriate tools and put them together to be able to model the effects of climate change on the environmental impact of the European dairy sector by 2050. To do so, this thesis is composed of the following chapters as shown in Figure 1.4:

- **Chapter 1** analyses and gives clear evidence of the interaction between climate hazards, their biophysical impacts, and their effect on the environmental impacts of the dairy sector. Elementary flows and connections on the interaction were connected and qualitatively described.
- **Chapter 2** describes the methods used in this thesis to make possible the in-depth analysis of the effects of climate change on the European dairy sector and evaluate changes in its environmental performance across different climate and geographical horizons by 2050. Here LCA, RA, and IO tables are described in detail.
- **Chapter 3** fills the gap in the knowledge by developing a model based on RA to estimate raw milk losses due to bovine mastitis, which is the most common disease affecting dairy farms worldwide, on European dairy farms across different regions and climate scenarios (i.e., SSP2-4.5 and the SSP5-8.5) by 2050.
- **Chapter 4** develops and tests a toolbox to quantify the intensity of climate hazards and their biophysical impacts identified in Chapter 1 as well as to estimate changes in the environmental performance of dairy farms. The RA model from Chapter 3 is part of the toolbox, and its result was incorporated into LCA as climate hazards lead to changes in the reference flows. In this chapter two case studies under contrasting climate conditions are selected to demonstrate the applicability of the toolbox: a Spanish dairy farm in the Mediterranean region of Europe and a Swedish dairy farm in the Northern of Europe.
- **Chapter 5** identifies site-specific adaptation strategies for avoiding those climate hazards detected in the previous chapter. Then, this chapter evaluates the net environmental cost of those site-specific adaptation strategies to identify win-win strategies, which are those that ensure food safety and offset the cost of climate hazards while doing it at a low environmental cost. In line with the previous chapter, here the same two case studies are considered.
- **Chapter 6** applies the developed toolbox in a company context. It supports the disclosure of the biophysical impacts that climate hazards pose to the dairy farms of the largest dairy cooperative in the world: Arla Foods, Denmark. In addition, the mathematical models from the toolbox that address raw milk losses from heat stress and

mastitis were transferred into a user-friendly application and distributed to the respective department within the cooperative.

- **Chapter 7** highlights the key findings of this thesis and provides reflections on the contribution of this research to European policies and industrial initiatives aimed at the dairy sector. Additionally, a recognition of the limitations of this research is also described in this chapter.

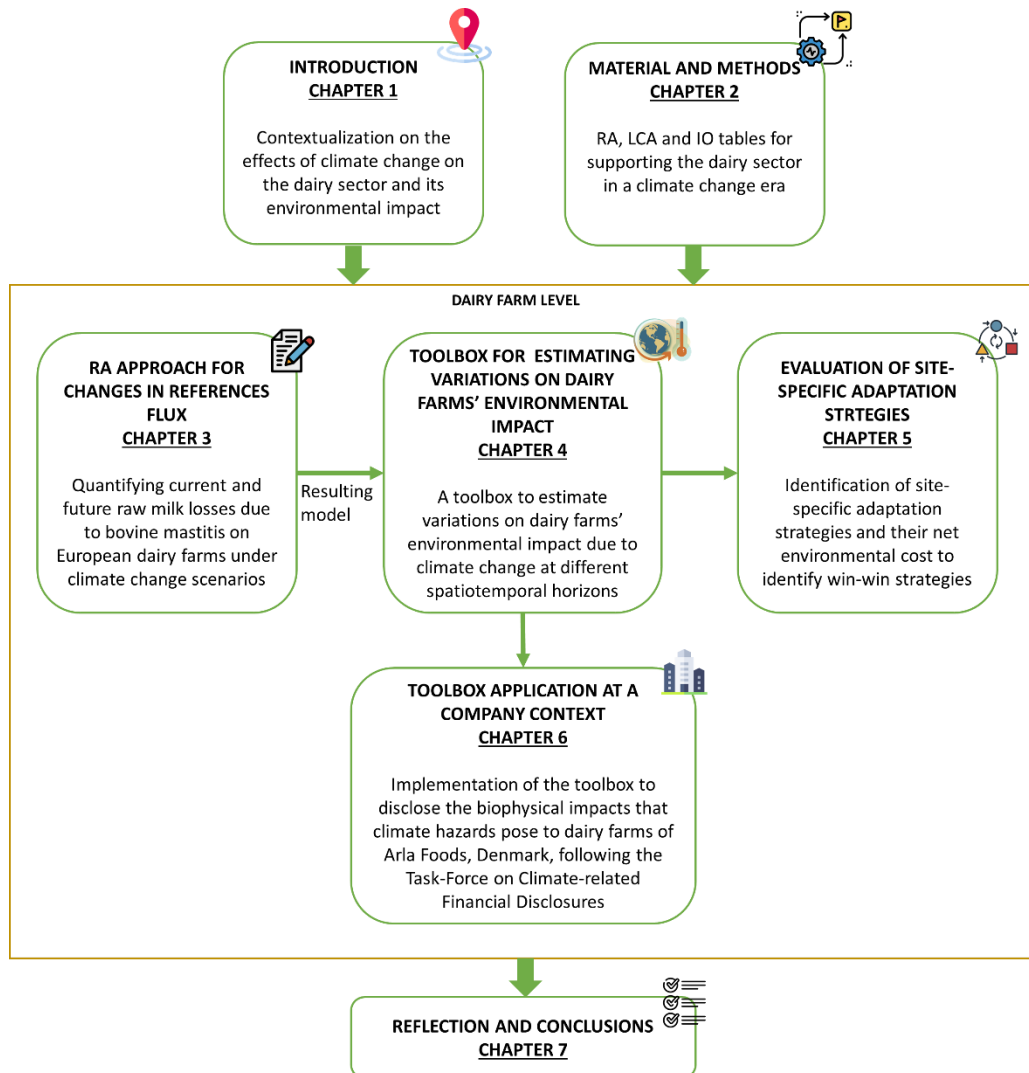


Figure 1.4. Structure of the thesis and description of the chapters.

2. MATERIALS AND METHODS

SUMMARY

This chapter gives an overview of the methods used in this thesis. Climate hazards and their biophysical impacts are expected to challenge the dairy sector as they may influence its environmental performance and food safety requirements, leading to an increase in food losses and waste. Which, in turn, can contribute to climate change and other environmental impacts.

Not a unique methodology is available to confront this complex challenge, so there is a need for an integrated framework that draws together methodologies and tools to address the environmental performance of the dairy sector in different geographical and temporal contexts, as well as that considers the related food safety requirements. Life Cycle Assessment, combining process and input-output based approach, together with Food Safety Risk Assessment are then used along this thesis and therefore presented here.

This chapter is built on Deliverables 5.5 and 5.6 from PROTECT-ITN that are available as open access:

- PROTECT-ITN (2022a). Deliverable D5.5: Integrated RA, LCA and Energy methodology, <http://www.protect-itn.eu/>.
- PROTECT-ITN (2022b). Deliverable D5.6: Application and validation of the combined methodology, <http://www.protect-itn.eu/>.

2.1 ENVIRONMENTAL EVALUATION METHODOLOGY

Life Cycle Assessment (LCA) is the systematic analysis of the potential environmental impacts of products or services during their entire life cycle. It has been implemented worldwide to quantify the environmental impacts of food supply chains (Grigoriadis et al., 2021; Notarnicola et al., 2017; Roy et al., 2009) and it has been widely used to evaluate the environmental performance of dairy products (Cortés et al., 2020; Djekic et al., 2014; Guzmán-Luna et al., 2021; Roibás et al., 2016b; Üçtuğ, 2019; Yan et al., 2011).

The International Organization for Standardization provides guidelines and requirements for conducting an LCA (ISO 14040, 2006; ISO 14044, 2006), which implies four phases that feedback (Figure 2.1) as described below:

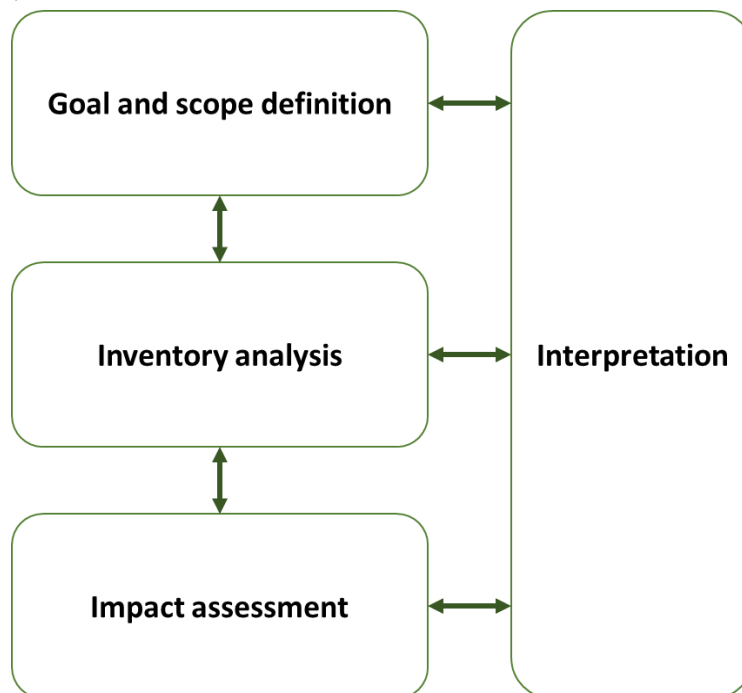


Figure 2.1. Phases of the Life Cycle Assessment adapted from ISO 14040 (2006).

Goal and scope definition: The aim of the study is here determined. The functional unit (FU), which aims to provide a quantitative description of the product under evaluation, as well as the reference flows, which refer to the specific product (and product parts) flows required to deliver the FU, are defined. Also, the data quality requirements are established, as they are critical to ensure the completeness and representativeness of the dataset of the assessment. The criteria are commonly defined based on data uncertainty, technological, geographical, and time-related representativeness. In addition, the system boundaries, including geographical and temporal boundaries, are stated at this phase. Impact categories relevant to the goal defined have to be selected and justified here, as well as the impact assessment methods used for their evaluation.

Inventory analysis: In this phase, a Life Cycle Inventory (LCI) is built by collecting all the input and output flows related to the product system. Based on data availability and requirements, two types of data are recognized:

- **Foreground data** (also named primary data) refers to the data directly collected or measured representative of the studied facilities.

- Background data (also named secondary data) refers to the data that is not directly measured or collected and thus, it is obtained from literature or databases, such as Ecoinvent v3.7 database (Ecoinvent, 2020) and IMAGE 3.0 (Stehfest et al., 2014).

LCI construction can follow three different approaches (Lenzen & Crawford, 2009; Nakamura & Nansai, 2016):

- A process-based analysis, which involves analyzing the individual processes involved in the production of a product or service. The data collected from this analysis include the inputs (such as raw materials, energy, and water) and outputs (such as emissions and waste) associated with each process. This information is used to create an LCI that quantifies the environmental impacts associated with each stage of the product's life cycle. This approach has been commonly used to assess the environmental performance of dairy products (EDA, 2018a).
- An Input-Output (IO)-based analysis, that considers the interdependence of productive sectors in the economy of a region or country. Inputs and outputs associated with the product or service under study can be traced in this type of analysis since data on the inputs and outputs of entire sectors are collected in the IO tables. They show the flows of goods and services between sectors, as well as, in some cases, the associated environmental impacts (Luo & Ierapetritou, 2020).

In the context of LCA, there are two types of IO tables, single-region IO (SRIO) and multi-region IO (MRIO) (Yang et al., 2017). The former is often used in LCA to estimate the environmental impacts associated with the production of a product or service within a specific region as it describes the economic transactions within a single region or country. SRIO tables are available for different countries all over the world (ADB, 2021; EStat, 2019; INE, 2019). The latter refers to MRIO matrixes that represent the global economy and are constructed by combining several SRIO tables from different regions or countries. MRIO matrixes are useful when the product or service being studied has a high degree of international trade, and when the system boundary of the LCA extends beyond a single region or country, as is the case of dairy farms that import crops.

FABIO (Food and Agriculture Biomass Input-Output), is an MRIO table that provides a detailed analysis of the agriculture biomass along global supply chains, allowing to trace the origin of a crop and its final user (Bruckner et al., 2019). FABIO is built on data from the UN Food and Agriculture Organization, covering 130 commodities and 191 countries from 1986 to 2013.

- A hybrid analysis, which is a combination of previous ones, aims at overcoming the limitations of both since it leverages the detailed information provided by process analysis and utilises the comprehensiveness of IO tables. For example, hybrid analysis is able to fill the lack of information related to crop origin for feedstock at dairy farms that might be unknown when collecting process-based inventory data. Besides, MRIOs are often aggregated at a national level, and thus, they may not capture the site-specific climate conditions of the particular location(s) under evaluation (Agez et al., 2020), such as the case of a dairy farm located in a dry region with limited water resources that may have different environmental performance than the average dairy farm at a national scale.

Impact Assessment: Life cycle impact assessment (LCIA) helps the interpretation of LCA studies by translating LCI into a limited number of environmental impact scores (Hauschild & Huijbregts, 2015). This is done by means of so-called characterization factors, that indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released). According to ISO 14040 (2006), the mandatory steps at this stage are:

- Selection of impact categories based on the goal and scope definition. Impact categories can be selected at a midpoint level¹ or endpoint level², being the two approaches complementary. The midpoint characterization has a stronger relation to the environmental flows and relatively low uncertainty, while the endpoint characterization provides better information on the environmental relevance of the environmental flows. But the latter is also more uncertain compared to the midpoint characterization factors (M.Z. Hauschild & Huijbregts, 2015).

The water-energy-food-ecosystem (WEFE) provides a comprehensive framework to highlight the strong interdependence between water, energy (sturdily linked to GHG emissions), food security, and ecosystems (including land), allowing to determine trade-offs and synergies for maintaining the integrity of ecosystems. In this context, global warming (GW), water use (WU), and land use (LU) have been recognized as significant for dairy farming, which are impact categories relevant to the WEFE nexus. They are described below (Huijbregts et al., 2017):

- Global warming: this impact category measures the potential of a substance to contribute to global warming, expressed in terms of the equivalent amount of carbon dioxide (CO₂) emissions over a specified time horizon.
 - Water use: this midpoint impact category measures the amount of water consumed by a product or service and it is measured as m³.
 - Land use: this impact category is linked to land occupation or transformation for agricultural, and it expressed as m² per year.
- Classification involves the assignment of the inventory data to a specific environmental impact category according to the potential impact of the input or output. The classification step ensures then that the inventory data is matched to the appropriate impact categories that are relevant to the study.
 - Characterisation: Here the selected environmental impact categories are quantified using a impact assessment method to obtain the environmental performance of the system under evaluation. Among the available methodologies, (Goedkoop et al., 2009) developed a life cycle impact assessment method called ReCiPe 2008 that provides harmonized characterization factors at midpoint and endpoint levels. ReCiPe 2016 (Huijbregts et al., 2017) updated it by providing characterization factors that are representative for the global scale, instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterization factors at a country and continental scale. Below the description of the three impact categories is given:
 - Global warming: To quantify this midpoint impact category, the ReCiPe (Huijbregts et al., 2017) method implements the IPCC (Intergovernmental Panel on Climate Change) 2013 method as it assess the global warming potential (GWP) of GHG emissions. Here the GWP quantifies the amount of the

¹ Characterization factors at the midpoint level are located somewhere along the impact pathway, typically at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category.

² Characterization factors at the endpoint level correspond to three areas of protection, i.e., human health, ecosystem quality and resource scarcity.

integrated radiative force increase of a GHG over a time horizon and it is expressed in CO₂ equivalent (CO₂e). So, the different GHGs emitted throughout the life cycle of the product can be compared on a common scale. In a 100-year horizon, which is the widely used period, the characterisation factors for methane and nitrous oxide are 34 and 298 kg of CO₂ per kg of substance, respectively.

- Water use: In the ReCiPe methodology, the water use impact category uses the concept of water scarcity measured in m³ of water consumed or withdrawn in a year. Water consumption refers to the amount of water that a watershed has lost, whereas withdrawn is translated into the water withdrawn from surface or ground sources without consider its return to the water body (Huijbregts et al., 2017).
- Land use: this impact category includes the amount of land use due to transformation or occupation and the corresponding potential impact on the quality and services of ecosystems. This category is expressed in m² per year as it looks to represent the number of species potentially lost due to a land use change during a period, which is commonly one year (Huijbregts et al., 2017).

In order to perform the characterisation step, softwares are available, such as Activity Browser v2.7.5 (Steubing, 2015). It is an open source graphical user interface for performing LCA, which provide advanced features such as parametrisation and scenario modeling (Bernhard Steubing et al., 2020). The latter feature is essential when comparing the environmental performance of a product or services among several scenario, as it is the case of this research.

Interpretation: Finally, the LCIA results are interpreted to identify possibilities to reduce the environmental impacts of the product or service under study. Depending on the goal and scope, some LCAs may also incorporate sensitivity analysis (i.e., assessing the robustness of the results), uncertainty analysis (i.e., estimating the degree of uncertainty in the results), or contribution analysis (i.e., identifying the sources of the environmental impacts) (Baumann & Tillman, 2004).

2.2 FOOD SAFETY RISK ASSESSMENT TOOL

Food safety is a priority along any food value chain, and thus, the presence of hazards (i.e., chemical, physical, and microbiological) is a contentious issue. Thus, food safety management is a key step to mitigate the risk of potential hazards and ensure safety along each stage. Food safety management can be achieved through the adoption of risk analysis, which is composed of three activities: Risk assessment (RA), risk management, and risk communication (FAO & WHO, 2006):

- Risk assessment (RA) is a systematic and scientific approach to identifying hazards, estimating their likelihood and consequences, and identifying uncertainties surrounding these estimates. By doing so, RA provides decision-makers with reliable and comprehensive information about the risks involved.

RA is composed of four steps (Codex Alimentarius Commission, 1999; FAO and WHO, 2006):

- Hazard identification involves identifying potential hazards (covering biological (e.g., bacteria and viruses), chemical (e.g., pesticides and antibiotics) and

physical hazards (e.g., metal and glass)) that might pose a risk to the system under study. It looks at giving an answer to the question:

What can be harmful?

- Hazard characterisation determines the negative effects that the identified hazards may have on health. Here different levels of exposure and the probability of harm that these hazards imply are considered. Dose-response assessments are commonly used to quantify the adverse health effects of these hazards. The question to be answered is:

What effects do the hazards cause?

- Exposure assessment estimates the extent and magnitude of exposure to a potential hazard. This step seeks as giving an answer to:

Who may be harmed?

At what level of exposure it may be harmful?

- Risk characterisation: The assessments from the three previous steps are considered here to evaluate the risk under several degrees of exposure and probability. It looks at answering:

Is a food-borne hazard likely to harm?

- Risk management refers to the process of taking informed decisions to manage and mitigate the risks based on the RA. Its goal is then to reduce the likelihood and impact of potential risks to an acceptable level.
- Risk communication involves sharing information about the estimated risks and defining risk management strategies with stakeholders, including decision-makers, affected parties, and the public. Its goal is then to provide clear and concise messaging to promote understanding among stakeholders.

Global warming is expected to promote the presence of microbiological hazards in food value chains, leading to an increase in losses and waste as products might not comply with food safety regulations (Misiou & Koutsoumanis, 2021). In an era of climate change, where meeting these regulations is a must and where industries have to align their production to climate and environmental targets, the integration of RA and LA is a promising approach.

The integration of RA into LCA is not a new practice and they have been already integrated into distinct fields in which four schools are recognized (i.e., chain perspective, risk assessment for life cycle hotspot, knowledge integration, and comparison and combination of results) (Guinée et al., 2017) as described below:

- Chain perspective analyses the value chain of substances required in the manufacturing of a product and this school focuses on the different applications that a given substance has in a geographic area. It allows analyse the site-specific risk to human health of the substance itself but also of all its applications.
- Risk assessment for life cycle hotspot occurs when first LCA identifies the most critical life cycle stage(s), and consecutively, RA is conducted at this stage(s) to evaluate the health risks to humans from the dominant chemicals identified.
- Knowledge integration integrates RA models in the LCIA stage of LCA, so specific characterization factors can be developed. This approach is widely used and enables the incorporation of impacts into the endpoint category of human health, which is covered by LCA.
- Comparison and combination of results conducts RAs and LCAs separately. Subsequently, their results, which are expressed in DALYs (i.e., Disability Adjusted Life Years), are compared or combined using a multicriteria decision analysis. This

approach is only appropriated when the endpoint indicator on damage to human health is considered in LCA as it provides the same unit (i.e., DALYs) by RA.

According to Feliciano et al. (2022), from the four approaches previously mentioned, the first two are only appropriate for non-food domains (e.g., synthetic chemicals or nanomaterials), whereas the last two can be applied in the food domain.

Following the strategy of the Knowledge integration school, the integration of RA into LCA can also be applicable to the LCI. The use of RA models can be useful to estimate food losses and waste as they are commonly disregarded or not quantified with the required level of detail in the LCI, leading to a change in the reference flows in LCA and an underestimation of the environmental impact. However, this approach within this school has not yet been explored as done in this research.

All in all, the integration of RA and LCA has yet to be explored further in the food domain. It is a promising approach in an era of climate change as it can support the design of win-win strategies that ensure food safety with a low contribution to climate change and other environmental impacts (Feliciano et al., 2022).

3. RISK ASSESSMENT FOR CHANGES IN REFERENCES FLUX

SUMMARY

Bovine mastitis is an infectious disease that causes udder inflammation and is responsible for raw milk losses across European dairy farms. It is associated with reduced cow milk yield and contributes to elevated Somatic Cell Count (SCC) in raw milk. *Staphylococcus aureus* is one of the most prevalent mastitis pathogens that cause subclinical and clinical mastitis and can be present as a coloniser bacterium in cows. Climate change and geographical variability may influence the prevalence of this pathogen.

This chapter quantifies raw milk losses due to bovine mastitis throughout the implementation of RA, and then, the results of RA helped to modify the respective reference fluxes of LCA. In this chapter, raw milk losses are quantified across dairy farms located across different European regions under different climate scenarios. An exposure assessment model and a stepwise probabilistic model were developed to predict potential cow milk yield reduction, *S. aureus* and SCC concentrations in the bulk tank milk at dairy farms. Baseline (i.e., present) and future climate change scenarios were defined, and the resultant concentrations of SCC and *S. aureus* were compared to the actual European regulatory limits. Across the three regions, raw milk losses ranged from 1.06% to 2.15% in the baseline. However, they increased up to 3.21% in the climate change scenarios when no on-farm improvements were considered. Regarding geographical variation, the highest potential milk losses were reported for the Mediterranean and the lowest for the Continental region. Concerning the fulfilment of the regulatory limits, the mean of *S. aureus* and SCC levels in milk did not exceed them either in any region or scenario. Nevertheless, when looking at percentiles, the 10th percentile remained above the limits of *S. aureus* in Atlantic and Mediterranean, but not in the Continental region.

The content of this chapter is constructed from a published scientific paper resulting from the academic secondment at University College Dublin under the supervision of Dr. Rajat Nag and Prof. Enda Cummins from the School of Biosystems and Food Engineering:

- Guzmán-Luna, P., Nag, R., Martínez, I., Mauricio-Iglesias, M., Hospido, A., & Cummins, E. (2022). Quantifying current and future raw milk losses due to bovine mastitis on European dairy farms under climate change scenarios. *Science of the Total Environment*, 833(155–149) <https://doi.org/10.1016/j.scitotenv.2022.155149>

3.1 INTRODUCTION

The dairy sector is a leader in the agricultural economy of the European Union (EU). In 2020, milk farmers across the EU produced 154 million tonnes of cow's milk (Eurostat, 2022), which is expected to increase (Bórawski et al., 2020). Even though milk is produced across all the EU member states, approximately 77% (119 million tonnes per year) of the total raw milk produced in the EU is located in seven countries (Eurostat, 2022). Bovine mastitis causes bacterial intramammary infections, and it is one of the most widespread global diseases that impact European dairy farms (Nalon & Stevenson, 2019). On dairy farms, the total raw milk losses due to mastitis can occur in two ways. On the one hand, this infection leads to a significant decrease in the cows' milk yield, being more pronounced in cows with clinical mastitis (where milk is typically discarded) than in cows with subclinical infection (Ingalls, 2001); on the other, this infection alters the raw milk quality, becoming unsuitable for human consumption and further processing (Gonçalves et al., 2018). The somatic cell count (SCC) is an indicator used in the dairy industry to determine the raw milk quality (Pantoja et al., 2009). Another relevant indicator is the total bacteria count (TBC), which determines hygienic on-farm conditions during milk production (Robles et al., 2020). Across European dairy farms, *Staphylococcus aureus* has been identified as one of the major bacteria that cause bovine mastitis (Mekonnen et al., 2018; More et al., 2013; Tegegne & Tesfaye, 2017). It can appear as a coloniser on cows (coM) and remain unnoticed without inflammatory symptoms. However, it can also transmit from cow to cow, turning into subclinical bovine mastitis (sM) or evolving into clinical mastitis (cM), where symptoms are visible in the latter (Wald et al., 2019; Wellnitz & Bruckmaier, 2012). Besides being a bacteria found in the cows' udders, *S. aureus* has also been found at dairy facilities such as on milking systems, bedding material, faeces and feed (Zadoks & Fitzpatrick, 2009).

The proliferation of pathogens is expected to benefit from the changes in climatic conditions (European Food Safety Authority, 2020) and, therefore, increase the microbial load in raw milk (Misiou & Koutsoumanis, 2021). In particular, the rise of average temperatures as a consequence of climate change around the globe (IPCC, 2014b) is expected to increase the prevalence of bovine mastitis among dairy herds and, consequently, contribute to higher raw milk losses (Jingar et al., 2014).

Projected climate change effects are not expected to occur uniformly worldwide. Across Europe, six biogeographical regions have been defined by the European Environment Agency (2017) depending on the climate change impacts and vulnerabilities, being the Mediterranean (i.e., southern Europe) one of the most vulnerable regions. This region is experiencing and is projected to continue experiencing temperature rises and a reduction of rainfall, mainly in summer, leading to droughts (EEA, 2017). Similarly, the Continental region (i.e., central and eastern Europe) will suffer from an increment of heat extremes and rainfall reduction during the summer, increasing the risk of drought. On the contrary, an increment of extreme precipitation events is projected to occur in the Atlantic regions (i.e., north-western Europe) (EEA, 2017).

Quality assurance of dairy products commences on the dairy farms, and thus, regulatory limits for SCC and *S. aureus* in raw milk have been set in Europe (European Commission, 2003, 2004). Both SCC and *S. aureus* load in raw milk have been widely studied previously (Jayarao et al., 2004; Kateřina et al., 2016; Malek dos Reis et al., 2013; Mekonnen et al., 2018; Naito et al., 2013; Wang et al., 2018), but none of these studies analysed the contamination pathway of

S. aureus from the dairy farm to the farm bulk tank milk (BTM), which includes the intramammary and environmental *S. aureus*.

Quantitative Microbial Risk Assessment (QMRA) is a tool that aims to develop knowledge of the spread and control of infectious diseases (Mitchel et al., 2021). QMRA is particularly useful in developing control strategies and evidence-based policy decisions through the lens of health risk. QMRA is not limited to human health risks; it can also be developed for animal and plant pathogens (Mitchel et al., 2021).

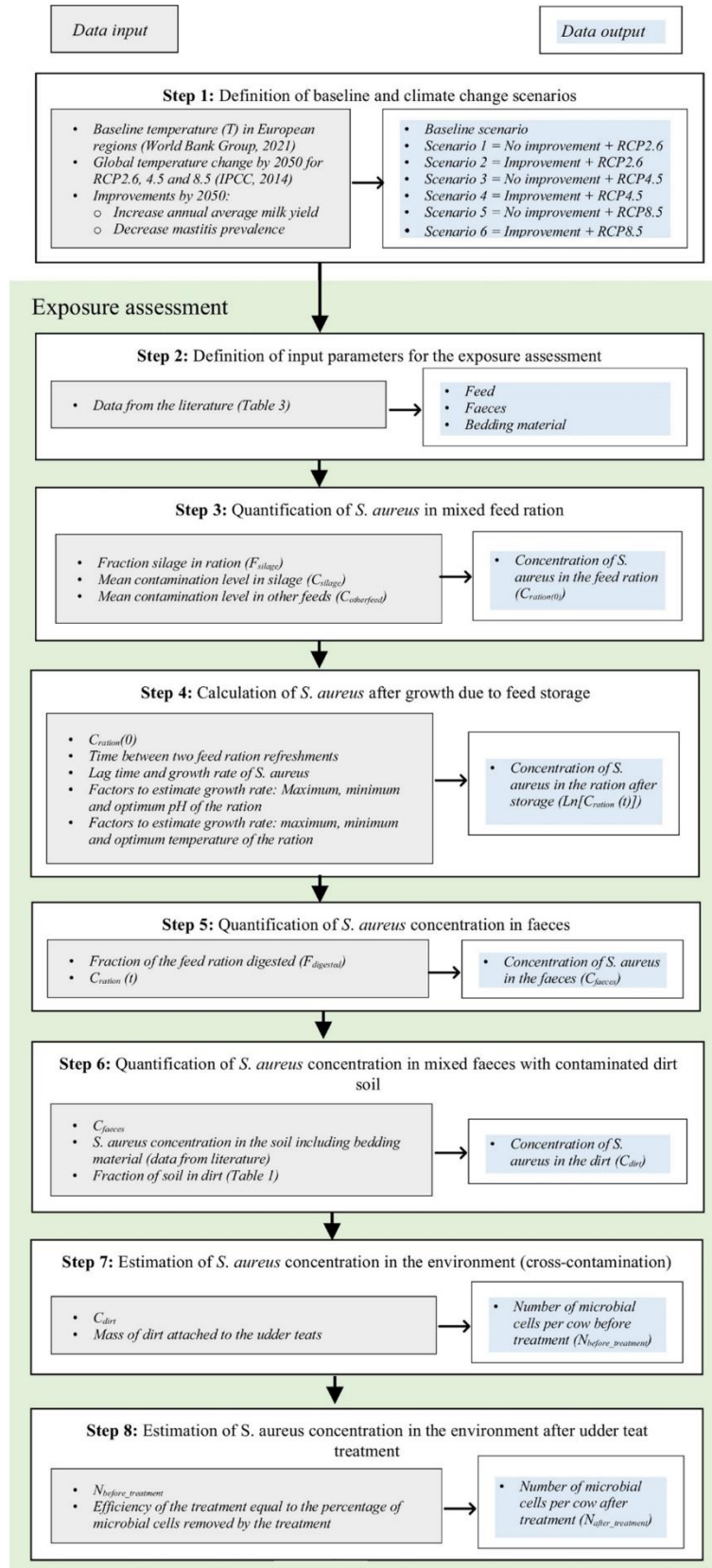
The overall hypothesis of this research is “Bovine mastitis may pose a threat to European dairy farms causing milk losses, which may change under projected climate change scenarios”. Hence, under climate change scenarios, this study aimed to predict the annual raw milk losses due to bovine mastitis across the main European milk producer regions. Climate change scenarios were considered to investigate the influence of temperature increment on the annual raw milk losses at dairy farms located in the Mediterranean, Atlantic and Continental. Herds were assumed to be comprised of 100 lactating cows in an indoor dairy housing system. Moreover, given the lack of studies that includes the complete contamination pathway of *S. aureus*, this research includes both the environmental and intramammary contamination of this pathogen from the dairy cow to the BTM.

3.2 MATERIAL AND METHODS

A model framework was developed, composed of an exposure assessment and a stepwise probabilistic model, to predict the annual raw milk losses based on the SCC and *S. aureus* concentrations at BTM under climate change scenarios (Figure 3.1). The total raw milk losses include losses due to (i) exceeding the *S. aureus* and SCC limits in BTM, (ii) losses due to a cow's milk yield reduction, and (iii) raw milk discarded due to cow with clinical mastitis. The model inputs, computations and simulated outputs used in the model framework are detailed in Table 3.1. Specific parameters affected by temperature increase due to climate change are marked with an asterisk in the same table. The framework begins by defining the baseline scenario and climate change scenarios by 2050 (step 1). Then, an exposure assessment adapted from Vissers et al. (2006) was performed to estimate the amount of *S. aureus* in the environment to which cows are exposed. In the exposure assessment section, the different production stages¹ involved at a dairy farm are included (steps 2 to 8). Later, a stepwise probabilistic model was necessary to estimate the annual mastitis prevalence (step 9) and predict the cows' milk yield reduction and SCC and *S. aureus* concentrations at BTM (step 10). Finally, to estimate the raw milk losses associated with not meeting the standards, the *S. aureus* and SCC concentrations in the different scenarios were compared to the regulatory limits set in the EU (step 11). A sensitivity analysis was performed to identify the most influential model's inputs and observe its influence on the predicted raw milk losses.



¹ Production stages refers to the sources and route of transmission of *S. aureus* at dairy farms. Six production stages are identified throughout the exposure assessment model.



Continued to next page

Symbols	Description and references	Model/distribution baseline	Units
T_{ration}^*	The temperature of the ration, which was assumed to be the same as the current shade temperature and varies depending on the region under study (World Bank Group, 2021a).	Atlantic: Uniform (min 3.3, max 18.3) Mediterranean: Uniform (min 4.2, max 21.9) Continental: Uniform (min 0.5, max 17.8)	°C
T_{min}	Minimum growth temperature (Medveov & Valk, 2012)	7	°C
T_{opt}	Optimal growth temperature (Medveov & Valk, 2012)	Uniform (min 37, max 40)	°C
pH_{ration}	The pH of the feed ration (Borreani & Tabacco, 2010)	4.1	
pH_{min}	Minimum growth pH (Medveov & Valk, 2012)	4	
pH_{max}	Maximum growth pH (Medveov & Valk, 2012)	9.8	
pH_{opt}	Optimal growth pH (Medveov & Valk, 2012)	Uniform (min 6, max 7)	
$F_{digested}$	Fraction of the feed ration digested (Lassey, 2007)	75	%
$F_{bedding}^1$	Fraction of bedding material in the dirt (Vissers et al., 2006)	Uniform (min 0, max 20)	%
$C_{bedding}$	Bedding material contamination level	Table 3.3	Log ₁₀ CFU g ⁻¹
M_{dirt}	Mass of dirt attached to the udder teats (Vissers et al., 2006)	1	G
$PT_{efficiency}^1$	% of spores removed without pre-treatment (Vissers et al., 2006)	Pert (30, 75, 90)	%
$AAMY^{2*}$	Data on annual average milk yield from a healthy cow (records provided by CLUN)	Lognormal (mean 12500, SD 1318.99)	L year ⁻¹
SCC_{wald}	Data on Somatic Cell Count from Wald et al. (2019) required in the binomial flag	Table 3.4	Cells mL ⁻¹
S_{wald}	Data on <i>S. aureus</i> concentration from Wald et al. (2019) required in the binomial flag	Table 3.4	CFU mL ⁻¹
MP_{aft_red}	Annual raw milk production by the herd considering milk yield reduction. Data on milk yield reduction per type of mastitis was retrieved from Sharma et al. (2011) and required in the binomial flag	Table 3.5	L year ⁻¹
Model outputs			
$C_{ration(0)}$	The concentration of <i>S. aureus</i> in the ration after mixing feed components (adapted from Vissers et al., 2006)	Eq. 1	CFU g ⁻¹
$C_{ration}(t)$	The concentration of <i>S. aureus</i> in the ration considering the effect of feed storage (adapted from Vissers et al., 2006)	Eq. 2	CFU g ⁻¹
C_{faeces}	The concentration of <i>S. aureus</i> in the faeces (adapted from Vissers et al., 2006)	Eq. 8	CFU g ⁻¹
C_{dirt}	The concentration of <i>S. aureus</i> in the dirt because of a mix of faeces and bedding material (adapted from Vissers et al., 2006)	Eq. 9	CFU g ⁻¹
$N_{before_treatment}$	Most probable number of <i>S. aureus</i> in cow's udders due to cross-contamination from dirt before treatment (adapted from Vissers et al., 2006)	Eq. 10	CFU
$N_{after_treatment}$	Most probable number of <i>S. aureus</i> in cow's udders after treatment (adapted from Vissers et al., 2006)	Eq. 11	CFU

Symbols	Description and references	Model/distribution baseline	Units
sM_{prev}^*	Prevalence of subclinical mastitis based on the temperature from each region	Eq. 12	%
cM_{prev}^*	Prevalence of clinical mastitis based on the temperature from each region	Eq. 13	%
SCC_{BTM}	Somatic Cell Count concentration in the bulk tank milk	Eq. 14	Cells mL ⁻¹
M_{yield_after}	Actual annual milk yield after considering cow milk yield reduction. Data from Sharma et al., (2011) was required	Eq. 15	L year ⁻¹
S_{BTM}	<i>S. aureus</i> concentration in the bulk tank milk, considering the load in the environment and the raw milk due to the intramammary infection	Eq. 16	CFU mL ⁻¹

3.2.1 Definition of baseline and climate change scenarios (step 1)

The baseline scenario was built on current average annual temperatures (T) representative of the regions (i.e., Atlantic, Mediterranean, and Continental) that deviated from the World Bank Group (2021). The climate change scenarios were constructed based on the Representative Concentration Pathways (RCP) developed by the Intergovernmental Panel on Climate Change (i.e., RCP 2.6, 4.5 and 8.5) (IPCC, 2014b). Unlike other emission scenarios, the RCPs project totals radiative forcing, considering the effect of efforts (e.g., international policies and agreements) to reduce greenhouse gas (GHG) emissions and mitigate climate change. Therefore, the RCP2.6 is considered a scenario with great mitigation efforts. RCP4.5 refers to an intermediate stabilised scenario, and RCP8.5 refers to a scenario where no efforts to reduce GHG emissions are made (IPCC, 2014b). Each of the mentioned RCP scenarios was split into two sub-scenarios (Table 3.2), assuming ‘on-farm improvements’ and ‘no on-farm improvements’.

Table 3.2. Description of the six climate change scenarios applied in this research.

	Temperature change by 2050 (°C)		
	RCP2.6 (+0.3 to 1.7) ^a	RCP4.5 (+1.1 to 2.6) ^a	RCP8.5 (+2.6 to 4.8) ^a
No Improvement	Scenario 1	Scenario 3	Scenario 5
Improvement	Scenario 2	Scenario 4	Scenario 6

‘On-farm improvements’ scenarios consider an increase in the annual average milk yield ($AAMY$) and a decrease in annual mastitis prevalence. The former results from the continuous efforts to increase the $AAMY$ through feeding strategies and genetic enhancement, which are expected to keep increasing in the near future (Bórawski et al., 2020). According to Reijs et al. (2013), there is a constant increment in the milk yield per dairy cow in different countries. By applying a linear model on the data on milk yield over the years, an increment of 50% by 2050 was projected compared to the $AAMY$ in 2019, obtaining an R^2 of 0.9. Thus, a projected $AAMY$ of 18800 (SD 1979) L year⁻¹ by 2050 was calculated. The latter results from farm enhancements such as improvement in udder health and novel mastitis treatments (IDF, 2018). These improvements reduced the rate of mastitis prevalence over the past years, and it is expected to continuously improve in the near term. However, data on the potential prevalence of mastitis by 2050 and historical records to predict it were not found. Thus, this study assumes a 10% reduction of annual prevalence by 2050, compared to the present prevalence.

Conversely, in the ‘no on-farm improvements’ scenarios, upgrades are not considered. The $AAMY$ remains stable in 12500 year⁻¹, and the annual mastitis prevalence increases by 10% due

to a rise in average global temperatures, leading to an increase of bovine mastitis (Jingar et al., 2014). The T change by 2050 is expected to vary amongst RCPs, so, Table 3.2 shows the corresponding increments for each scenario.

3.2.2 Input parameters definition for the exposure assessment model (step 2)

This step includes collating information for the input parameters in the exposure assessment model for *S. aureus* concentration in the dairy facilities environment. Three sources of contamination of *S. aureus* were identified (bedding material, silage, and the concentrated feed), and the number of *S. aureus* on each of these sources was retrieved from the literature (Table 3.3). Silage includes grass and maize ensilage. Also, the material used for the cows' bed is assumed to be straw and sawdust since both are the materials most used by dairy farmers (Leso et al., 2020).

Table 3.3. Data collation on the number of *S. aureus* for each input parameter of the model.

Input	Symbol	Raw data (CFU g ⁻¹)	Reference
Bedding material	$C_{bedding}$	3.1×10^8	(Rendos et al., 1975)
Bedding material	$C_{bedding}$	4.9×10^7	(Rendos et al., 1975)
Bedding material	$C_{bedding}$	2.2×10^9	(Rendos et al., 1975)
Bedding material	$C_{bedding}$	$10 - 8 \times 10^6$	(Bradley et al., 2018)
Bedding material	$C_{bedding}$	$1.4 (\pm \text{SD } 2.5) 10^8$	(Black et al., 2014)
Bedding material	$C_{bedding}$	$6.9 \log_{10}$	(Hogan et al., 1990)
Bedding material	$C_{bedding}$	$5.5 \log_{10}$	(Hogan et al., 1990)
Bedding material	$C_{bedding}$	$7.7 \log_{10}$	(Hogan et al., 1990)
Silage	C_{silage}	<10	(CESFAC, 2007; CLUN, 2021)
Concentrated feed	$C_{concentrated}$	<10	(CESFAC, 2007; CLUN, 2021)

3.2.3 Quantification of *S. aureus* when feed components are mixed (step 3)

Step 2 addresses the first production stage at dairy farms, consisting of the potential contamination of *S. aureus* in the cows' feed ration. The feed ration is a mix between concentrated feed and silage. However, the process of mixing potentially results in a contaminated feed ration with pathogens (Hope et al., 2009). Eq. 1 was applied to quantify the initial *S. aureus* concentration in the feed ration ($C_{ration(0)}$) after mixing the silage and concentrated feed, in which the obtained unit is CFU g⁻¹.

$$C_{ration(0)} = F_{silage} \times C_{silage} + (1 - F_{silage}) \times C_{concentrated} \quad (1)$$

where F_{silage} is translated as the fraction of silage in the cows' diet ration, which varies depending on dairy farmers' practices and dairy production systems (i.e., confined indoor and grazing outdoor). The value for the F_{silage} for an indoor system was obtained from the farmers' opinion (Table 3.1). Regarding C_{silage} and $C_{concentrated}$, they refer to the most probable number of *S. aureus* in silage and concentrated feed, respectively. Respective data was deviated from the allowable limits of *S. aureus* in ruminant feed production (Table 3.3) according to the Guide of Feed Sanitization Standards (CESFAC, 2007). This guide is commonly used among farmers from the cooperative to reference quality controls at dairy farms.

3.2.4 Calculate the effect of pathogen growth due to feed storage (step 4)

During feed storage, the growth of *S. aureus* can occur, and it can be influenced by environmental conditions such as temperature, and consequently, affected by the climate

change scenarios. Thus, to calculate the pathogen concentration in the ration after storage ($\ln[C_{ration}(t)]$), Eq. 2 was retrieved from Vissers et al., (2006). The obtained unit is $\ln \text{CFU g}^{-1}$.

$$\ln[C_{ration}(t)] = \ln[C_{ration}(0)] + \mu \times A_n(t) - \ln\left(1 + \frac{e^{\mu \cdot A_n(t)} \times t}{e^{\ln(C_\infty/C_{ration}(0))}}\right) \quad (2)$$

where $C_{ration(0)}$ is the initial concentration previously calculated in Eq. 1; μ is the microbial growth in the feed ration, and it is calculated based on the Baranyi and Roberts model (Baranyi & Roberts, 1994); A_n is equal to the time between two feed ration refreshments (t), which are obtained in hours; e is a mathematical constant equal to 2,718; C_∞ refers to the maximum level of contamination achievable in the feed ration, which according to Vissers et al., (2006), it is assumed equal to $8 \log_{10}$ pathogen g^{-1} .

Also, Eq. 3 was needed to solve μ in Eq. 2. It followed a gamma concept model since temperature (Eq. 4) and pH (Eq. 5) effects are considered separately. *S. aureus* prefers an optimum temperature (T_{opt}) that ranges from 37°C to 40°C and a minimum temperature (T_{min}) of 7°C. The T_{ration} was considered equal to the environment temperature. Thus, the average temperature was used from each biogeographical region for the baseline and different climate change scenarios (Step 1). Concerning the pH ($\gamma(pH)$), this mastitis pathogen prefers an optimum pH (pH_{opt}) that ranges from 6 to 7. It tolerates a minimum and maximum pH of 4 and 9.8, respectively (Medveov & Valk, 2012). The pH from the ration (pH_{ration}) was 4.1 (Borreani & Tabacco, 2010).

$$\mu = \gamma(T) \times \gamma(pH) \times \mu_{opt} \quad (3)$$

$$\gamma(T) = \left(\frac{T_{ration} - T_{min}}{T_{opt} - T_{min}}\right)^2 \quad (4)$$

$$\gamma(pH) = \left[\frac{(pH_{ration} - pH_{min}) \times (pH_{max} - pH_{ration})}{(pH_{opt} - pH_{min}) \times (pH_{max} - pH_{opt})}\right] \quad (5)$$

Lastly, Eq. 6 (Vissers et al., 2006) solves $A_n(t)$ in Eq. 2, in which the obtained unit is hours. λ refers to the lag time, which is equal to 1, and t (in h) refers to the time between one feed ration and the next refreshment, which depends on dairy farmer's practices, so data from CLUN was used (Table 3.1).

$$A_n(t) = t + \frac{1}{\mu} \ln\left(\frac{e^{-\mu t} + q_0}{1 + q_0}\right) \quad (6)$$

$$q_0 = \frac{1}{e^{\lambda \cdot \mu} - 1} \quad (7)$$

3.2.5 Effect of animal digestion in the *S. aureus* concentration of faeces (step 5)

The next production stage is associated with the *S. aureus* concentration in cows' faeces. Microorganisms can survive the ruminant digestion process and return to the environment throughout the animals' excretion. Eq. 8 quantifies the *S. aureus* concentration in the faeces (C_{faeces}) in CFU g^{-1} . To do so, the fraction of the feed ration that is digested ($F_{digested}$) is retrieved from Lassey (2007), which is equal to 75%.

$$C_{faeces}(t) = \left(\frac{1}{1 - F_{digested}}\right) \times C_{ration}(t) \quad (8)$$

3.2.6 Effect of mixing the faeces with soil resulting in contaminated dirt (step 6)

Another production stage is linked to a mix between faeces and bedding material, which are commonly mixed due to the natural movement and displacement of the cows resulting in contaminated dirt. Following Vissers et al. (2006), Eq. 9 estimates the *S. aureus* concentration in the contaminated dirt (C_{dirt}) in CFU g⁻¹.

$$C_{dirt} = F_{bedding} \times C_{bedding} + (1 - F_{bedding}) \times C_{faeces} \quad (9)$$

where $F_{bedding}$ refers to the fraction of bedding material in the dirt, as shown in Table 3.1. The pathogen concentration in bedding material ($C_{bedding}$) was calculated based on the values extracted from the literature, as shown in Table 3.3, and C_{faeces} was obtained previously from Eq. 8.

3.2.7 Evaluation of the cross-contamination from dirt to udder teats (step 7)

This production stage refers to the *S. aureus* contamination resulting in cross-contamination from the dirt to the dairy cows' teats. Thus, Eq. 10 quantifies the number of microbial cells per cow (stated in CFU) before a common treatment that dairy farmers carry out to rinse off as much as possible the dirt on teats:

$$N_{before_treatment} = M_{dirt} \times C_{dirt} \quad (10)$$

where M_{dirt} is the mass of dirt stuck to the cows' teats (in g) and obtained from Vissers et al. (2006), as shown in Table 3.1, while C_{dirt} was previously calculated in Eq. 9.

3.2.8 Effect of the treatment process of udder teats (step 8)

In this step, the final concentration of *S. aureus* to which cows are exposed environmentally was calculated. During the production stage, teats are rinsed off, and microorganisms are removed on the cows' teats. Eq. 11 estimate the number of microbial cells per cow ($N_{after_treatment}$) after the treatment process, obtaining a value in CFU.

$$N_{after_treatment} = PT_{efficiency} \times N_{before} \quad (11)$$

where $PT_{efficiency}$ refers to the treatment efficiency based on the percentage of microorganisms removed. The $PT_{efficiency}$ was assumed 75%, as reported by Vissers et al. (2006) (Table 3.1).

3.2.9 Annual mastitis prevalence (step 9)

An estimation of the annual mastitis prevalence was required to calculate the concentration of intramammary *S. aureus*. Since the study looks at the effect of climate change on raw milk losses due to mastitis, the prevalence of each mastitis was calculated in function of temperature. To do so, the sM prevalence (sM_{prev}) was estimated with a linear model, using the reported data on temperature and subclinical prevalence by Yang et al. (2012) and obtaining the result in percentage. The following equation (Eq. 12) was obtained with an R² equal to 0.6:

$$sM_{prev} = 7.734(T)^{0.4262} \quad (12)$$

Similarly, the cM prevalence (cM_{prev}) was calculated with a linear model, implementing data on temperature and clinical prevalence reported by Jingar et al. (2014) and obtaining the result in percentage. The following equation (Eq. 13) was obtained with an R² equal to 0.9:

$$cM_{prev} = 0.0026(T) - 0.0263 \tag{13}$$

Later, T (Eq. 12 and 13) was substituted by the average annual temperature representative of each region (Atlantic, Mediterranean, and Continental) in the baseline and climate change scenarios.

Lastly, due to a lack of data on the prevalence of mastitis provoked by coloniser *S. aureus*, the prevalence was estimated with two conversion factors. These factors were obtained from the subclinical-to-coloniser (70:12) and clinical-to-coloniser (18:12) ratios provided by Wald et al. (2019). Then, a uniform distribution was applied by using both conversion factors.

3.2.10 Binomial flag (step 10)

A binomial flagging method (Vose, 2000) was used to estimate the *S. aureus* and SCC concentration in the BTM. This approach is built on the binomial distribution, and it can be useful to resolve problems and estimate the probability of success of a trial, such as done by Coffey et al. (2009). They implemented the binomial flagging approach to estimate the presence of Aflatoxin B1 in maize, finding 51 samples positive out of 139. Translating it to the present research, the mastitis prevalence previously calculated together with the binomial flag allowed the calculation of the number of infected cows out of a herd of 100. A second binomial flag was applied only for the infected cows to determine the number of cows with cM (labelled as category 3), sM (labelled as category 2) and/or coM (labelled as category 1) (Table 3.4), while healthy cows were labelled as category 0. Once the number of cows within each category was estimated, data on the concentration of SCC and *S. aureus* per cow was derived using data from Wald et al. (2019) (Table 3.4). It allowed the calculation of the SCC (SCC_{BTM}) and *S. aureus* (S_{BTM}) concentrations per mL in the BTM. Also, the cows' milk yield reduction was estimated since these concentrations depend on how much each cow contributes to the BTM (Table 3.5).

Table 3.4. *S. aureus* and SCC concentration in the milk corresponding to each type of bovine mastitis. Adapted from Wald et al. (2019). Data on the column of SCC concentration (SCC_{wald}) is used in Eq. 14 and data on the column of *S. aureus* concentration (S_{wald}) is used in Eq. 18.

Flag label	SCC concentration (cells mL ⁻¹)				<i>S. aureus</i> concentration (CFU mL ⁻¹)		Distribution	
	Median	Mean	SD	Distribution	Min	Max		
3	cM	>10 ⁶	2.18×10 ⁶	1.58×10 ⁶	Lognormal(2.18×10 ⁶ , 1.58×10 ⁶)	10 ⁵	10 ⁶	Uniform(10 ⁵ ,10 ⁶)
2	sM	200000 - 500000	1.00×10 ⁶	1.21×10 ⁶	Lognormal(1.00×10 ⁶ , 1.21×10 ⁶)	10 ³	10 ⁴	Uniform(10 ³ ,10 ⁴)
1	coM	≤100000	4.50×10 ⁴	3.30×10 ⁴	Lognormal(4.50×10 ⁴ , 3.30×10 ⁴)	10 ³	10 ⁴	Uniform(10 ³ ,10 ⁴)

The SCC_{BTM} was estimated by Eq. 14 and stated in cells mL⁻¹. Cows with clinical mastitis were excluded since they are assumed to be separated from the rest of the herd, and their milk does not enter the BTM.

$$SCC_{BTM} = \frac{[(Cow_{coM} \times SCC_{wald}) \times M_{yield_after}] + [(Cow_{sM} \times SCC_{wald}) \times M_{yield_after}]}{MP_{aft_red} \times 1000} \times 1000 \tag{14}$$

Where the total number of cows with coloniser (Cow_{coM}) and subclinical mastitis (Cow_{sM}) in the herd were multiplied by the respective SCC concentration stated by Wald et al. (2019) (SCC_{wald}) in Table 3.4. Later, this contribution was multiplied by the actual annual milk yield after considering cow milk yield reduction (M_{yield_after}) (L year⁻¹) using equation 15:



$$M_{yield_after} = AAMY - MYR_{mastitis} \quad (15)$$

Where $AAMY$ refers to the annual average milk yield ($L \text{ year}^{-1}$) from healthy cows considering data provided by CLUN (mean 12545, SD 1319). $MYR_{mastitis}$ refers to the milk yield reduction according to the type of bovine mastitis (sM or coM), calculated from Sharma et al. (2011) (Table 3.5), who provided the respective milk yield reductions based on SCC concentration in the raw milk per cow.

Finally, the total concentration of SCC (cells year^{-1}) from sM and coM was divided by the annual raw milk production in $L \text{ year}^{-1}$ (MP_{aft_red}), in which a reduction of the cows' milk yield due to bovine mastitis in the herd was also considered.

Table 3.5. Milk yield reduction per cow depending on its SCC concentration in the raw milk per cow. Adapted from Sharma et al. (2011).

SCC (cells mL^{-1})			Flag label of the type of mastitis	Milk yield reduction (l 305-days $^{-1}$) ^a
Minimum	Mid-point	Maximum		
0	1250	17000	0	0
18000	25000	34000	0	0
25000	50000	70000	1	0
566000	800000	1130000	2	726
1131000	1600000	2263000	3	907

In order to cover the whole contamination pathway, Eq. 16 estimates the S_{BTM} (stated in CFU mL^{-1}) by adding up the *S. aureus* load to which cows are exposed in the facilities environment (S_{env}) and the *S. aureus* concentration in the milk (S_{sa}) coming from the intramammary infection. Cows with clinical signs were also excluded here.

$$S_{BTM} = S_{env} + S_{sa} \quad (16)$$

The first summand is given by Eq. 17 and stated in CFU mL^{-1} , where Cow_{coM} and Cow_{sM} refer to the number of cows with either coloniser or subclinical mastitis in the herd, $N_{after_treatment}$ to the number of microbial cells a cow is exposed to after treatment and is retrieved from step 7 (Eq. 11 in CFU) and MP_{aft_red} to the total milk produced in $l \text{ day}^{-1}$ after milk yield reduction, as mentioned in Table 3.5.

$$S_{env} = \frac{(Cow_{coM} + Cow_{sM}) \times N_{after_treatment}}{MP_{aft_red}} \quad (17)$$

The second summand is given by Eq. 18 and is also stated in CFU mL^{-1} . S_{sa} the calculation is similar to SCC_{BTM} , but considering data on *S. aureus* from Table 3.4, where the total number of cows either with coloniser (Cow_{coM}) or subclinical mastitis (Cow_{sM}) were multiplied by the respective *S. aureus* concentration estimated by Wald et al. (2019) (CFU mL^{-1}). The contribution of *S. aureus* per mL of raw milk was multiplied by the actual annual milk yield once cow milk yield reduction was considered (M_{yield_after}).

$$S_{sa} = \frac{[(Cow_{coM} \times S_{Wald}) \times M_{yield_after}] + [(Cow_{sM} \times S_{Wald}) \times M_{yield_after}] \times 1000}{MP_{aft_red} \times 1000} \quad (18)$$

3.2.11 Total raw milk losses under current and climate change scenarios (step 11)

To obtain the raw milk losses related to not meeting the quality standards, the S_{BTM} and the SCC_{BTM} were compared to the regulatory limits for raw milk intended for processing in the EU: i.e., 400 000 cells mL^{-1} of SCC (EC, 2004) and 2 000 CFU mL^{-1} of *S. aureus* (EC, 2003). The raw milk losses due to milk yield decrease were calculated from the difference between the total milk production assuming all cows are healthy and the total milk production with reduced milk yield due to bovine mastitis, divided by the total milk production to obtain a percentual value. The milk yield reduction from clinical cows was excluded since their milk production is directly considered a loss.

3.3 RESULTS AND DISCUSSION

3.3.1 Current raw milk losses due to bovine mastitis

As a result of step 9, the highest annual prevalence of *S. aureus* mastitis was estimated for the Mediterranean. For this region, the proportions of each mastitis category were 22.7% for sM, 0.6% for cM, and 2.5% for coM (detail values per biogeographical region and mastitis category in [supplementary Figure S1](#)). The prevalence of mastitis varies across Europe and precise percentages on the bovine mastitis prevalence are not available since national recording systems on cows' welfare and mastitis rates are unavailable in most European countries. However, according to the literature, the annual mastitis prevalence in Europe ranges from 8 to 48% per herd (EFSA, 2009; IDF, 2018), matching the annual prevalence calculated in the present research. Similarly, step 10 showed the highest annual concentration of *S. aureus* and SCC throughout the whole contamination pathway for the Mediterranean region, 1.5×10^3 CFU mL^{-1} and 2.0×10^5 cells mL^{-1} , respectively (Figure S2 and Figure S3 in [supplementary material](#)).

The results of the annual cumulated raw milk losses are shown in detail in Figure 3.2. In a baseline scenario and across the three regions, the average annual raw milk loss due to bovine mastitis caused by *S. aureus* was 1.44%. In order to validate the calculated raw milk losses, the results of this research were compared to reported values. Houben et al. (1993) estimated the cumulated milk yield losses due to bovine mastitis, ranging from 0.5 to 2.0% when the cows were during their first lactation. The prevalence of mastitis used in that study was 13.7% (SD 10.3%). Another study found a similar percentage (i.e., 0.5%) when the prevalence of mastitis ranged from 18.1 to 27.4% Myllys & Rautala, (1995). The percentages of mastitis prevalence calculated in the present study align with the values used in the present research, which vary from 21.7 to 30.5%. In a more recent study, Heikkilä et al. (2018) quantified the raw milk losses due to bovine mastitis caused by *S. aureus*. They estimated a value of approximately 4.3% across Finnish dairy farms. The slight difference between the outcome found in that research and this research is attributed to the different annual mastitis prevalence selected by the authors, ranging from 72% for subclinical mastitis to 28% for clinical mastitis. They assumed higher values than the used in the present research.

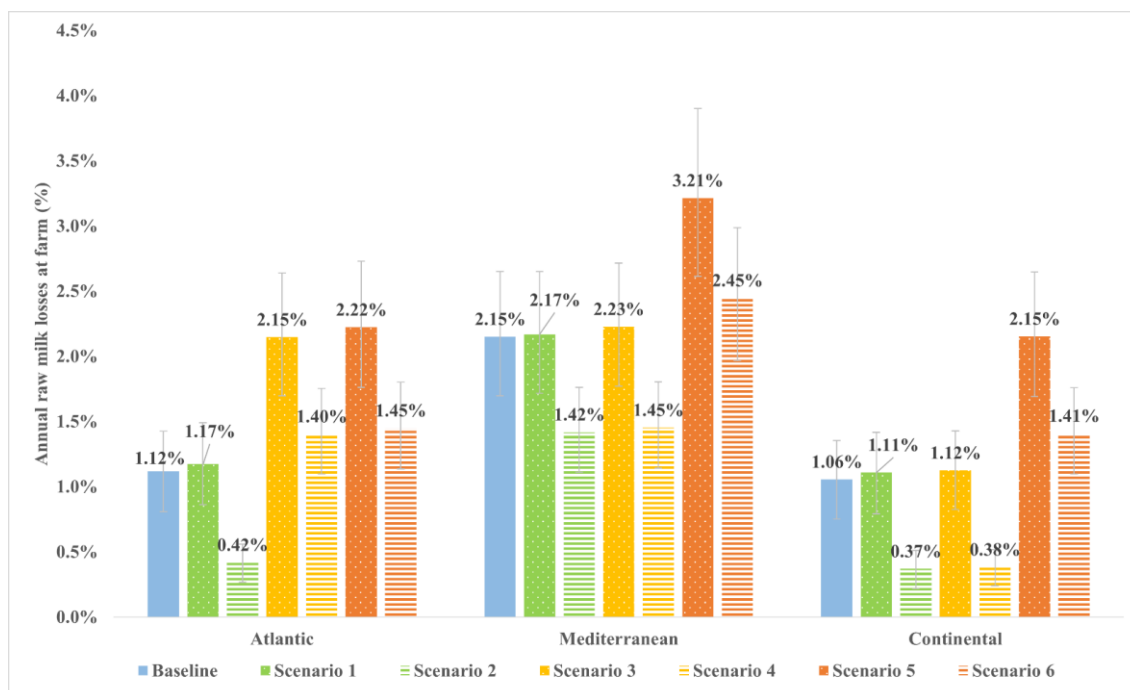


Figure 3.2. Predicted percentage of raw milk losses from the cumulated annual milk yield reduction due to bovine mastitis.

3.3.2 Future raw milk losses due to bovine mastitis under climate change scenarios

Mastitis prevalence was one of the computations influenced by the modification of temperatures according to each RCP (i.e., 2.6, 4.5 and 8.5). As a result of step 9, the highest annual prevalence of mastitis was also observed for the Mediterranean in all the climate change scenarios since temperatures in this region are higher than in the Atlantic and Continental regions. As a result, the proportions for each mastitis category increased for this region and different scenarios. In a pessimistic climate change scenario without farm improvements, the proportions increased up to 25.4% for sM, 1.6% for cM and 3.5% for coM due to a rise of temperature by 2050 (detail values per biogeographical region and mastitis category in [supplementary Figure S1](#)). On the contrary, they dropped to 15.4%, 1.6% and 2.5%, respectively, as an effect of the on-farm improvements. Similarly, the highest annual *S. aureus* and SCC concentrations were also presented in the Mediterranean region, increasing up to 1.8×10^3 CFU mL⁻¹ and 2.3×10^5 cells mL⁻¹, respectively, in scenario 5. On-farm improvements have a significant positive effect on the *S. aureus* and SCC concentration, dropping to 1.0×10^3 CFU mL⁻¹ and 1.4×10^5 cells mL⁻¹, respectively, when scenario 6 is considered (Figure S2 and Figure S3 in the [supplementary material](#)). As a consequence, in the same scenario, annual raw milk losses reached only 2.45% in dairy farms located in the Mediterranean. However, when no on-farm improvements are considered, raw milk losses increased by 3.21% (Figure 3.2).

Due to the lack of similar studies, the comparison of the predicted raw milk losses for future scenarios obtained in this chapter was not possible.

3.3.3 Sensitivity analysis

A sensitivity analysis was conducted to investigate which input parameters had the largest influence on the predictive model, which quantified the *S. aureus* from the environment and cross-contamination. According to Figure 3.3, $C_{bedding}$ resulted as the most influential parameter on the concentration of *S. aureus* in the BTM, showing a positive correlation

coefficient of 0.96. The value used for the *S. aureus* concentration in the bedding material contributes significantly to the pathogen concentration due to environment and cross-contamination. It explains that the concentration of *S. aureus* from the environment obtained in all the scenarios remains similar. Another input parameter of importance is $F_{bedding}$, reaching a positive correlation coefficient of 0.20. Besides, temperature and pH were also part of the sensitivity analysis; however, both showed an insignificant influence, 0.01 and 0, respectively. In other words, the bedding material is an important source of bacteria load, and the material used at dairy facilities influences the *S. aureus* load on cows' udder and teats. Later, a negative correlation coefficient of 0.13 was found for $PT_{efficiency}$, which means this parameter can reduce the *S. aureus* contamination on cows' udders. For the sensitivity analysis, the values of these three input parameters were changed towards a worst and optimal scenario by selecting the lowest and the highest values. In an optimal scenario, the value of *S. aureus* concentration after treatment was reduced to 7.9×10^{-2} CFU lactating cow⁻¹ year⁻¹, compared to the value obtained in the baseline scenario 3.02×10^7 CFU lactating cow⁻¹ year⁻¹. Conversely, in the worst scenario, the *S. aureus* concentration value increased to 3.08×10^8 CFU lactating cow⁻¹ year⁻¹ compared to the baseline scenario.

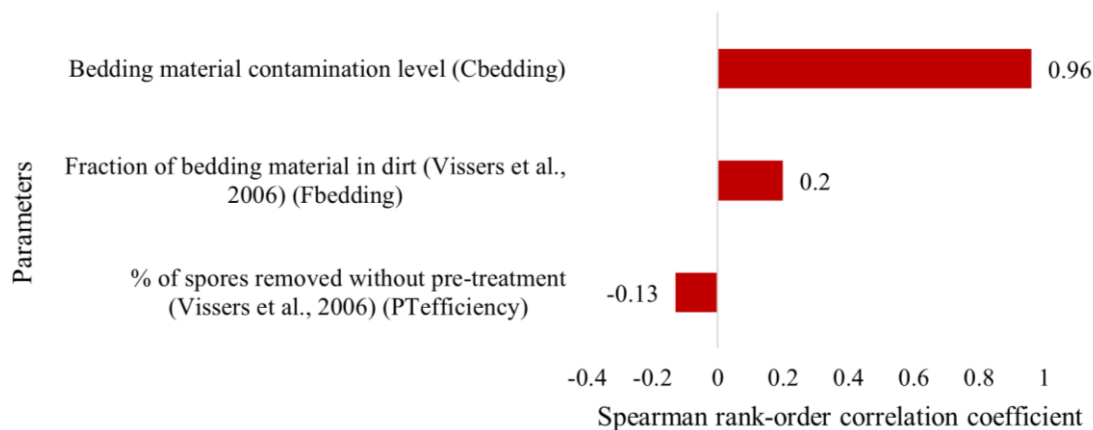


Figure 3.3. Effect of input parameters in the exposure assessment model used to calculate the environmental *S. aureus* at dairy facilities (Spearman Rank correlation coefficient).

3.4 RECOMMENDATION

This research aimed to predict the future influence of climate change on milk losses due to bovine mastitis caused by *S. aureus*. The results make it possible to establish the magnitude and direction of the expected consequences on milk production under the future effects of climate change. If unchecked, a potential increase in the prevalence of mastitis is anticipated due to global warming, resulting in milk loss increases, which are anticipated to be more pronounced in the Mediterranean and Atlantic regions of Europe. The predictive model and the results of this research will serve as a framework for farmers to design corrective measures to reduce milk losses due to mastitis. The model may also help farmers and policymakers make the right decision for future adaptation plans to counter climate change scenarios.

Global warming is expected in the near future by 2050 (IPCC, 2021); however, dairy farmers can modify on-farm parameters to cope with this potential increase in the prevalence of mastitis. This study demonstrates the positive effect of farm improvements in reducing bovine mastitis. According to the IDF (2018), one way to reduce mastitis will be to develop

new mastitis treatments. However, medicaments to prevent and treat mastitis can enter in the environment (Guo et al., 2021) and potentially lead to an environmental impact (Guzmán-Luna et al., 2021). Other alternatives to reduce the prevalence of mastitis on farms in the future also need to be considered. Based on the sensitivity analysis of this study, bedding material significantly influences the concentration of *S. aureus* in raw milk. The reason is that bedding material carries mastitis pathogens to which the udders are exposed, causing bovine mastitis. In this context, the use of low moisture and clean bedding materials could become more important and be an effective strategy to help control potential contamination on cows under climate change conditions. In addition, periodic and more frequent cleaning of animal waste and hygiene practices on the farm are recommended. Bovine mastitis will mean lost profitability on farms due to the loss of raw milk due to the inefficient use of resources used for its production (Halasa et al., 2007).

Mastitis in dairy farms has been shown to have a significant environmental impact. For instance, the prevalence of this disease leads to increased greenhouse gas emissions per unit of product (Hospido & Sonesson, 2005; Mostert et al., 2019; Vida & Tedesco, 2017). In addition, the dairy sector looks at adapting to the future effects of climate change, but another challenge is to reduce its emissions. This sector is part of climate action and is committed to reducing GHG emissions from the European Union by 2050 (EDA, 2019). Therefore, in addition to designing adaptation plans to climate change that guarantee animal welfare and food quality, the environmental consequences must also be considered.

3.5 CONCLUSIONS

The present research aimed to predict the annual raw milk losses due to bovine mastitis considering several climate change scenarios using a risk assessment approach. Therefore, a stepwise probabilistic model was developed and proposed. To the best of our knowledge, this is the first time that the complete contamination pathway of *S. aureus* is covered by including all the on-farm production stages and the different sources of *S. aureus* exposure. Also, this is the first probabilistic model that can explain the influence of each input parameter of the process on the overall outcome. One of the challenges in developing the present model was the lack of studies that partially cover the contamination pathway of *S. aureus* from the farm to the BTM. Instead, they only tracked the *S. aureus* concentration of different on-farm spots and unit operations without covering all of them in the same study.

The predicted annual raw milk losses varied across regions and scenarios, being the Mediterranean the region that experiences the largest percentage loss in the baseline and climate change scenarios. For the baseline scenario, the annual losses ranged from 1.06% to 2.15% across all regions. For the future climate change scenarios, the annual raw milk losses varied from 1.17% to 3.21% across all regions when no on-farm improvements were assumed, whereas the losses dropped from 0.37% to 2.45% when on-farm improvements were considered. Bedding material contributes significantly to the concentration of *S. aureus* on-farm, and it is an important parameter to focus on for mastitis control programmes. The main cause of raw milk losses was not attributed to losses associated with exceeding quality standards but a reduction in the subclinical and coloniser cows' milk yield. The largest milk yield reduction was found in cows with clinical mastitis. Cows with coloniser and subclinical mastitis present lower milk yield reduction. However, unlike cows clinically infected, these cows are commonly milked, and their milk may enter the BTM due to the lack of infection physical symptoms. Thus, cows with subclinical and coloniser mastitis contribute to the two types of raw milk losses

found on the farm. The outcome of the present study will allow farmers to assess and predict potential raw milk losses under climate change scenarios and help identify adaptation plans to reduce the impact of climate change on milk yield loss.

4. TOOLBOX FOR ESTIMATING VARIATIONS ON DAIRY FARMS' ENVIRONMENTAL IMPACT

SUMMARY

Climate change has already affected and will continue to affect European dairy farms, the most climate-vulnerable stage in the dairy value chain. Climate hazards cause biophysical impacts in dairy farms unevenly across regions and climate scenarios. In turn, these biophysical impacts influence the dairy farm's environmental impact since the foreground and background systems of their activities are modified.

In this chapter, six hazards intensified by climate change and their biophysical impacts at the dairy farm level are addressed (i.e., water stress, floods, crop pest infestation, climate variability, cow heat stress, and cow diseases). The resultant changes in the environmental impact of dairy farms are estimated. To do so, a toolbox, which is composed of several types of data sources, is developed to convert given data into meaningful information on the impacts of climate change on dairy farms and their environmental impact across different geographical and temporal horizons. In this chapter, the toolbox is tested in two case study regions with different climatic conditions: Spanish dairy farms located in the Mediterranean and Swedish dairy farms located in the Northern region under current and future climate change conditions by 2050. Not surprisingly, dairy farms across the Mediterranean will be the most impacted when compared with dairy farms in the North. The contribution analysis carried out identified raw milk losses caused by cow heat stress and cow diseases as responsible for the rise in global warming potential and water depletion, while crop pest infestation and climate variability are responsible for the rise in land occupation. By integrating already available as well as adapted models, with different levels of complexity and computational requirements, the developed toolbox allows for exploring the possible scenarios that European dairy farms will face and for understanding of how climate change will affect them and their environmental performance.

The content of this chapter is built from a submitted scientific paper in the Journal of Cleaner Production:

- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2023). A toolbox to estimate variations on dairy farms' environmental impact due to climate change at different temporal and geographical horizons. *Journal of Cleaner Production* (submitted).

4.1 INTRODUCTION

The European dairy sector continues its transition to meet the ambitious environmental targets set for 2050: turning this sector into a climate-neutral (net-zero greenhouse gas (GHG) emissions) sector while promoting efficient land and water (EDA, 2019). Such transition aims to deal with the complex nexus between water, energy, food, and land (Carmona-Moreno et al., 2019); however, it is subject to climatic conditions, being challenged by climate hazards posed by climate change. Climate hazards modify ecosystems and threaten the dairy products value chains, where the primary production (i.e., raw milk production and required crop provision) is the most affected stage (Guzmán-Luna et al., 2022). There, climate hazards affect both the biological (i.e., dairy cows and crops) and the physical systems (i.e., water, soil, and atmosphere) (Rojas-Downing et al., 2017). In turn, the resultant biophysical impacts will modify the environmental impact per unit of raw milk produced. Climate hazards from climate change and their biophysical impacts will not be present uniformly across the world or Europe (IPCC, 2022), and thus, how climate hazards will affect the dairy farm's performance will also vary geographically. Across Europe, typically five biogeographical regions are defined based on their projected impacts of climate change, being the Mediterranean (i.e., southern Europe) the most vulnerable compared to the rest (i.e., Atlantic (i.e., Western Europe), mountain regions, northern Europe), and continental (i.e., central and eastern Europe) (EEA, 2017).

In a previous study (Guzmán-Luna et al. 2021), the interaction between the effects of climate change and the environmental impacts of the dairy value chain (with focus on the farm stage) were analysed. Elementary flows and connections between climate hazards, their biophysical impacts and dairy farm environmental impacts were qualitatively captured. Climate variability, crop pest infestation, and floods were identified as climate hazards that will change yield and geographical distribution of crops. Water stress was another relevant climate hazard that will affect ground and surface water availability for cattle and irrigated crops. Moreover, cow heat stress and cow diseases are two climate hazards that will lead to higher raw milk losses. These losses account for the raw milk that is never produced, as cow milk yield is reduced, and raw milk quality aspects, as cow diseases increase the pathogen load and somatic cell count in raw milk, becoming inappropriate for human consumption. Therefore, there is a clear interaction between the effects of climate change and the environmental impact of the dairy value chain. Climate hazards and their biophysical impacts have an effect on the environmental impact of the primary production stage, both directly at the foreground system (e.g., amount of water required on-site) as well as indirectly at the background system (e.g., water supply mix) (Guzmán-Luna et al. 2021). However, quantifying the changes in the Life Cycle Inventory (LCI) is quite complex, due to the large number of climatic and non-climate factors involved (i.e., technological improvements, market shifts, regulation transition), and their interconnections. In addition, expertise in specific software and tools are needed to manipulate available data and being able to produce information on the impacts of climate change at different geographical and temporal horizons. Also, LCI changes quantification becomes complex due to the high degree of uncertainty present in projected data for climate change scenarios, as well as the existent knowledge gaps on the estimation of climate hazards and their biophysical impacts on dairy farms across different regions and climate scenarios. One of the knowledge gaps identified is information on raw milk losses caused by cow heat stress and cow mastitis across the different biogeographical regions in Europe under different climate scenarios.

Despite the complexity and uncertainties, it is relevant to understand how the environmental performance of the most vulnerable stage (i.e., primary production) will be

impacted by climate change to meet the environmental targets by 2050. The objective of the present chapter is to develop and test a toolbox to estimate the intensity of climate hazards across European dairy farms, evaluate their biophysical impacts at this stage, and translate given biophysical impacts into potential changes of the dairy farm's environmental performance. The toolbox structure and sources of data are described in section 4.2. Section 4.3 demonstrates its usefulness by testing it in dairy farms located across two biogeographical regions (i.e., Spanish dairy farms located in the Mediterranean region and Swedish dairy farms located in the Northern region of Europe) under climate conditions representative of two temporal windows (i.e., 2020 and 2050); and translates the LCI changes into environmental impacts and examines the individual contribution of each climate hazard considered. Finally, section 4.4 of this chapter describes the limitations of the toolbox regarding availability of data and information and present uncertainty on the implemented models, and section 4.5 outlines conclusions.

4.2 METHODS: TOOLBOX STRUCTURE AND DATA SOURCES

To translate climate hazards and their biophysical impacts into changes in the environmental performance of the dairy farm due to future effects of climate change, a Life Cycle Assessment (LCA) approach was implemented. LCA consists of four steps (ISO 14040, 2006; ISO 14044, 2006) that include the goal and scope definition, where (in short) the system is defined in terms of the functional unit (FU) and system boundaries. Then, the LCI creates an inventory with the collection of all inputs (i.e., material and energy resources) and outputs (i.e., products, coproducts, waste, and emissions) over the life cycle of a product or service based on the FU. Next, in the life cycle impact assessment (LCIA), the LCI is translated into a set of potential environmental impacts. Finally, in the interpretation step, the results from the previous steps are summarized, analysed, and discussed.

This toolbox can be embedded into the LCI phase as it allows to generate theoretical LCIs that account for the future biophysical impacts of climate hazards across different geographical horizons and climate scenarios. In addition, as reference flow are expected to be affected by the increase of raw milk losses, the toolbox allows the definition of theoretical reference flow that accounts for raw milk losses from cow heat stress and diseases.

The toolbox (Figure 4.1) is composed of three modules where different data sources (i.e., simulation models, tools, software, and literature) are employed and they generate information on climate hazards and their impacts on a regional level or even site-specific level. As impacts of climate change are geographically and climatic scenario unequal, the selected data sources must meet two criteria: i) cover different geographical locations and ii) cover different time windows under several climate scenarios. When such type of data was not found, it had to be generated either by placing together existing models or by developing them specifically for the dairy farm under study. The first module defines the geographical and climatic context of the case study regions. The second module estimates the intensity of the climate hazards and their biophysical impacts by 2050 across dairy farms under study. The third module collects the perceptual changes in the LCI caused by the biophysical impacts of climate hazards, except for floods (i.e., dashed line in Figure 4.1) as later explained in section 4.2.2.1.

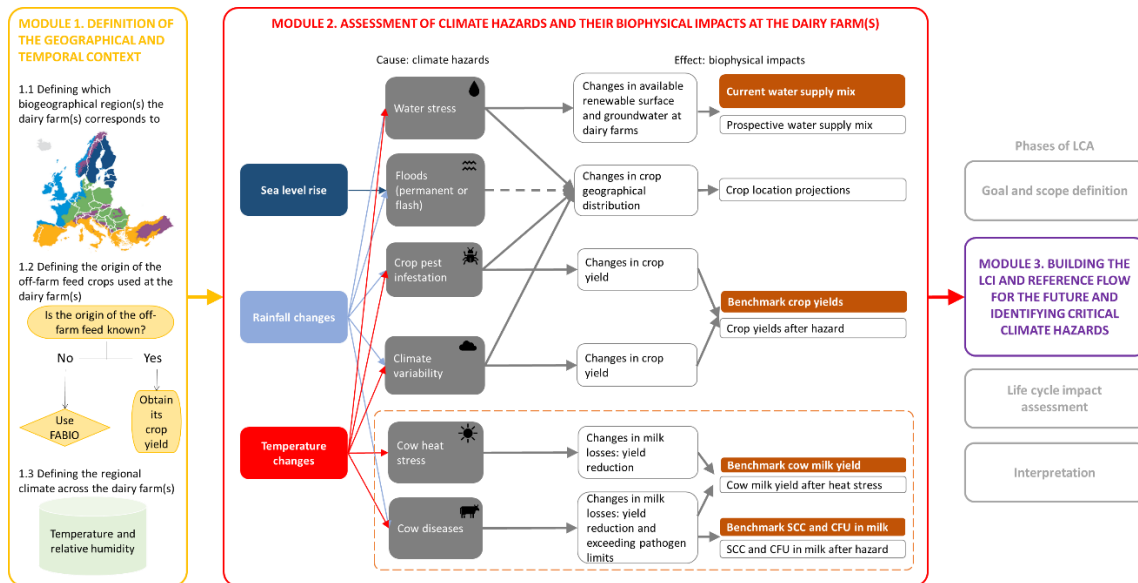


Figure 4.1. Toolbox to estimate changes in the environmental performance of dairy farms due to climate hazards and their biophysical impacts under different climate and geographical horizons, and its incorporation in LCA. Climate hazards (grey boxes) within orange dashed box are addressed with models that were specifically generated in this chapter, the rest are addressed with available data sources.

4.2.1 Module 1: Definition of the geographical and temporal context

This module defines the geographic and temporal context based on the location of the dairy farm(s). It allows to determine the climatic conditions in a given time and space contexts.

4.2.1.1 Geographic context: biogeographical regions across Europe

Defining which biogeographical region(s) the dairy farm(s) corresponds to is the first step in Module 1. In Europe, five regions were defined based on how they will be affected by climate change (EEA, 2017, 2019):

- The Mediterranean region (in orange colour in Figure 4.1) is the most vulnerable to climate change. This region is vulnerable to heatwaves, droughts, wildfires, disease vectors, water scarcity, and extreme weather events, leading to negative biophysical impacts on agriculture.
- The Atlantic region (in light blue colour in Figure 4.1) is anticipated to experience heavy precipitation events, sea level rise and riverine floodings.
- The Continental region (in green colour in Figure 4.1) is projected to suffer from an increase of average temperatures, heatwaves, and droughts mainly during summer. In addition, this region will be also affected by flash floodings due to heavy rains and river overflow during winter.
- The Mountain region (in purple colour in Figure 4.1) is expected to experience a rise of average temperature, leading to a melting of ice layers, and shrinking of glaciers and increasing the likelihood of rockfalls and landslides in certain places.
- The Northern region (in dark blue colour in Figure 4.1) is anticipated to experience heavy precipitation events, leading to floodings. Also, temperature conditions are projected to improve, which triggers in a rise of farmland yield.

4.2.1.2 Geographic context: origin of imported crops to the dairy farm(s)

As second step within Module 1, defining the origin of the off-farm feed crops used at the dairy farm(s) is carried out. When such origin remains unknown, the multiregional input and

output (IO) model FABIO (Food and Agriculture Biomass Input-Output) (Bruckner et al., 2019) is recommended as it allows to trace crops from their origin to the final consumer (i.e., dairy farms).

FABIO's code was extracted from the github¹ of the author of this IO model, being the use of computational programming required due to the large size of FABIO, as it contains 130 commodities and 191 countries from 1986 to 2013. To narrow FABIO down to the European dairy farm context and to the commodity of interest (i.e., cow raw milk), a filtering step was defined and applied (code included in the github of the author of this chapter²). Besides, allocation was also needed as FABIO jointly reports the crops that go to the primary production stage (i.e., dairy farms) and the processing stage (i.e., dairy plants), making impossible to differentiate both destinations. To solve this, the obtained list of crops was revised, and crops were allocated according to the authors expertise and knowledge. This detailed analysis of crops is required as cows' feed is one of the main contributors to the total environmental impact of dairy value chains (Djekic et al., 2014; Üçtuğ, 2019).

4.2.1.3 Temporal context: regional climate across the dairy farm(s)

Within Module 1, the temporal context is defined based on the regional climate conditions representative of 2020 and 2050, the two temporal horizons analysed. In this chapter, climate normals, i.e., statistical averages of weather data calculated for a specific period of time which provide an accurate description of the typical climate across a region, were used following the recommendations of the WMO (2017, 2021) to define the regional climate conditions by 2020 and 2050. Climate normals are typically updated every 10 years being 30-year the commonly period covered (for example, 1991 to 2020); however, for future climate normal the reference period has been shorten to a 20-year window since climate variability is expected to increase due to climate change (IPCC, 2013; World Bank Group, 2021b). The toolbox requires of four climate variables, and these are extracted as climate normals from the following sources: maximum temperature, minimum temperature, and precipitation from the World Bank Group (2021) and relative humidity from NASA (2021). To define the climate by 2020, historical climate normals of these two climate variables for the period of 1991-2020 are taken. This type of climate normals are built on observed and historical data from weather stations. To describe the climate by 2050, projected climate normals for the period 2040-2059 are obtained. This kind of climate normals are derived from the global climate model so-called Coupled Model Intercomparison Project Phase 6 (WCRP, 2019). The future climate in 2050 also depend on the chosen scenario: Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSPs describe the different possible socio-economic trends in the world, whereas the RCPs consider different levels of radiative forcing and describe different GHG concentration trajectories at different temporal horizons as a result of those socio-economic trends. While the RCPs and SSPs are different concepts, both are interconnected to create a framework for exploring the range of possible futures under different socioeconomic and emissions pathways. Thus, the SSP-RCP scenarios consists of the possible combinations of the SSPs and RCPs. The most optimistic scenario is the SSP1-1.9, whereas the most pessimistic is the SSP5-8.5 (IPCC, 2022). Among all the available SSP-RCP scenarios, the present chapter tests the toolbox with a particular scenario as explained in section 4.3. But other scenarios can be used within the toolbox at the convenience of the end-user.

¹ https://github.com/martinbruckner/fabio_v1.git

² <https://github.com/paolaguzmanluna>

4.2.2 Module 2: Assessment of climate hazards and their biophysical impacts

This module quantifies the intensity of climate hazards, and the corresponding biophysical impacts across the geographical and temporal context defined previously. Available data sources were used to generate information on the following climate hazards: water stress, floods, crop pest infestation and climate variability, as described in section 4.2.2.1. However, for two climate hazards, no data was available to address heat stress and cow diseases across different regions, temporal windows, and climate scenarios, so these data were generated as described in section 4.2.2.2.

4.2.2.1 Available data sources

The first climate hazard in Figure 4.1 is water stress. As it is a site-dependent hazard (Pfister et al., 2009), Aqueduct 3.0, a tool based on Geographical Information Systems (GIS), is used to define the water stress level across regions (WRI, 2022). GIS is a geospatial data source that creates, manages, and visualizes georeferenced data in multilayers, able to screen and analyse site-specific complex environmental challenges (Eccles et al., 2019; ESRI, 2022; Rong & Fenech, 2007). In Aqueduct 3.0, water stress is measured as the ratio of total water withdrawals from four sectors (domestic, industrial, irrigation, and livestock) to available renewable surface and groundwater supplies (Hofste et al., 2019) and expressed in percentage from 0 (no stress) to 100% (high stress). Values greater than 100% mean that no groundwater and surface water is available to satisfy the needs of the sector of interest, and thus, other water sources, such as external (e.g., inter-basin transfer) or non-conventional (e.g., reused water and desalinated water), must be resorted. Water stress is then linked to the regional water supply mix (WSmix). In the toolbox, the WSmix model from Leão et al. (2018) and the prospective water supply mix (P-WSmix) model from Leão et al. (2019) are used for the present and future regional water mixes to define the background data of the water used on-farm (i.e., for cleaning activities and cow drinking) and off-farm (i.e., for irrigation).

Regarding to the second climate hazard in Figure 4.1, flood risk, a differentiation was made between permanent and flash floods. The former is caused by sea level rise and implies the inundation of deltas, loss of wetlands, marshes, and saltwater intrusion, while the latter is caused by heavy precipitation events and brings the destruction of crops and a washing away of the land, affecting the availability of cow feedstuff. Data from Aqueduct 3.0 (Ward et al., 2020) was used to identify current and future potential areas at risk of permanent floodings as it represents floods as inundation depth in a range from 0 to 50 decimetres across coastal areas of Europe; while data from the European Environment Agency (EEA, 2014) was used to identify current and future potential areas at risk of flash floodings. Both types of floods might lead to changes in the geographical distribution of crops provision worldwide. However, projections on the future distribution of crops are complex and remain uncertain (Mahaut et al., 2022) as they not only depend on floods risk but also on many other biophysical factors (e.g., land-use change, soil suitability, water availability, crop pest presence, climate suitability) and non-biophysical factors (e.g., regulation transition). Thus, changes in the geographical distribution of crops remains out of the scope of this research due to the lack of data.

Crop pest infestation and climate variability lead to crop yield variation. Data from FAOSTAT (2022) were used for the current crop yields, being them available by the biogeographical regions present in Europe and across the world. Percentage changes of the crop yields grown on-farm were estimated with Aquacrop (FAO, 2022). It is a model that simulates the crop yield based on given climatic conditions such as minimum temperature, maximum temperature, precipitation, relative humidity, evapotranspiration, and CO₂ concentration in the atmosphere. These data are obtained from Module 1 of the toolbox (i.e.,

section 4.2.1.3). The percentage changes of grass yields from the baseline to the future are obtained from Carozzi et al. (2022). Then, the percentage change of crop yields grown outside of Europe are obtained from IPCC (2022).

4.2.2.2 Generation of additional information

Heat stress of animals is another climate hazard that will affect dairy farms unevenly across regions and climate scenarios depending on temperature and relative humidity changes, affecting milk yields and milk losses. To the best of our knowledge, no previous quantification of regional cow milk yield decline due to present and future heat stress has been done; so, to fill this gap, two equations were placed together:

$$THI_{month,i} = (1.8 \cdot T_{max,i} + 32) - (0.55 - 0.0055 \cdot RH_i) \cdot (1.8 \cdot T_{max,i} - 26) \quad (1)$$

Where: $THI_{month,i}$ is the Temperature Humidity Index of month i , $T_{max,i}$ the maximum temperature (°C) of that month, and RH_i its ambient relative humidity (%).

At present, THI (Eq. 1) is the most widespread indicator applied to assess the degree of heat stress to which cows are exposed (NRC, 1971). Here, the resultant THI is used to quantify the number of months under heat stress across selected regions for present and future scenarios.

Cow milk yield decline begins when the THI threshold (THI_{thr}) is exceeded; so, when the $THI_{month,i}$ exceeds the THI_{thr} , that month is identified as a month under heat stress. Eq. 2 (St-Pierre et al. 2003) is then applied over the stressed months to estimate the annual milk losses (ML_{hs}), stated as percentage.

$$ML_{hs} = AAMY - \sum_{i=1}^n 0.0695 \cdot D (THI_{month,i} - THI_{thr})^2 \quad (2)$$

Where: $AAMY$ refers to the average annual milk yield per cow (stated in kg of FPCM) and D is the fraction of a day where THI is higher than THI_{thr} , which is fixed as 0.33 (i.e., 8 hours a day) according to St-Pierre et al. (2003).

Present THI_{thr} was set up at 68 as reported by Hempel et al. (2019) and validated by dairy companies; while future THI_{thr} was stated also as 68 when no on-farm improvements were considered but increased to 72 when on-farm improvements (i.e., breed genetic improvement) were assumed. For present $AAMY$, data should be taken from the particular farm(s) under study; and for future $AAMY$ an increment of 50% by 2050 is assumed based on potential on-farm improvements such as breed genetic improvement (Guzmán-Luna et al., 2022).

Cow heat stress also modifies raw milk quality, which might lead to additional raw milk losses; however, these additional losses are beyond the scope of this chapter in which only changes in milk quality due to cow diseases are included. Among them, mastitis, an infectious disease that causes udder inflammation, is considered one of the most common and widespread disease responsible for significant raw milk losses (Nalon & Stevenson, 2019). To account for present and future milk losses due to mastitis across different regions and climate scenarios, the framework developed by Guzmán-Luna et al. (2022) was used. It combines an exposure assessment and a stepwise probabilistic model that requires current and future temperature data and incorporated future on-farm improvements, such as increase of raw milk due to breed genetic or more efficient mastitis preventive treatments to remove spores on udders. The

framework is composed of an exposure assessment and a stepwise probabilistic model that required current and future temperature data and incorporated future on-farm practices. The framework focused on *Staphylococcus aureus*, one of the most prevalent pathogens that cause bovine mastitis. Thus, raw milk was considered lost when it exceeded the *S. aureus* and somatic cell count regulatory limits and when the cow milk yield was reduced. Detailed information on the framework can be found on Guzmán-Luna et al. (2022), and the resultant annual milk losses are also quantified as percentage.

4.2.3 Module 3: Building the LCI and reference flow for the future and identifying critical climate hazards

The third module of the toolbox collects the quantified inventory changes to build the theoretical LCI of the future scenario (i.e., 2050) based on the present inventory (i.e., 2020). Then, also in the third module, the LCI changes are translated into environmental impacts by performing a life cycle-based assessment. It allows to observe percentage changes in the environmental impact of the dairy farm from the reference to the future scenario. To translate the LCI into environmental impacts, the FU was set as 1.0 kg of FPCM produced at the dairy farms under study in this chapter. Also, as part of any LCIA phase, an impact assessment method was selected, and in this case, the ReCiPe Midpoint (H) was used (Huijbregts et al., 2017). Here three impact categories were selected out of all the ones proposed by this impact assessment method to show the applicability of the toolbox: global warming (GW), water use (WU), and land use (LU). But more impact categories can be included in the assessment at the convenience of the end-user toolbox.

Non-climate hazards, such as energy transition, regulatory transition, modification in consumption and dietary patterns, also have an effect on the environmental impact of the primary production stage (Guzmán-Luna et al., 2021). However, these types of hazards are out of the scope of this study and only energy transition is included. Thus, the current and future electricity mix of the country where the dairy farm under study belongs to are considered as it modifies its background data. This information is obtained from the European Commission (2016) to align it with the current and future water supply mixes obtained from Leão et al. (2018).

4.3 TOOLBOX APPLICATION

To show the applicability of the described toolbox, it is tested in two case studies located in two different biogeographical regions (section 4.2.1.1) under climate conditions by 2020 and 2050. Within the Mediterranean and Northern region, respectively, Spain and Sweden are included in the top-10 largest producers of raw milk in Europe, contributing 4.5% (7.4 Mt) and 1.7% (2.7Mt) to the total European production in 2020 (Eurostat, 2022). Spain will not be hit by climate change equally: its Mediterranean region will be the most affected, where the Catalanian region is the largest cow milk producer with 10% (i.e., 0.7 Mt) of the total Spanish milk production in 2020 (FENIL, 2022; MAPA, 2022). Sweden is located between the Northern and Mountain regions, but the raw milk production is concentrated across the Northern one (Krizsan et al., 2021).

Regarding the temporal context (section 4.2.1.3), the future climate scenario selected is SSP2-4.5 scenario among all available. It is recognized as a plausible scenario with stable economic development and where GHG emissions decline by 2040, and as a result, the global temperature increased on average by 1.4 °C by 2050 (IPCC, 2022).

To build the theoretical LCI of the future scenario (i.e., 2050) by using the toolbox, a reference inventory (i.e., 2020) is required for selected case studies, which assumes that it already accounts for the biophysical impacts of climate change. So, the LCI reported by Egas et al. (2020) was used as it corresponds to a dairy farm located in the Mediterranean region of Spain (i.e., Catalanian). At this dairy farm, raw milk is produced under a confinement dairy production system and cows' feed is rich in barley, wheat, maize, and alfalfa, which are grown in Spain, and soybeans in which their origin is not reported (Egas et al., 2020). In addition, the LCI reported by Arla Foods (2022) was used since it corresponds to an Swedish dairy farm in the Northern region. Here the LCI was built from the average values of 1 799 dairy farms across this region where milk is produced under organic and conventional farming systems. The cows' feedstuffs include grass, maize whole crop silage, fodder beets, grains of barley, wheat, oats, beet pulp, molasses, beans, peas, and rapeseed meal, which are produced in Sweden. Also, feedstuffs include soybean meal, and in this case, their origin is reported (Arla Foods, 2022b). The use of these two LCIs is a representation to demonstrate the applicability of the toolbox.

Both inventories (Table 4.1) were built in accordance with the Product Environmental Footprint Category Rules (PEFCR) (EDA, 2018) and the International Dairy Federation guidelines (IDF, 2015)³. Besides, a data quality check was performed by the authors of the LCIs to guarantee the technological, geographical, time representativeness, precision, and uncertainty of the data according to EDA (2018).

Table 4.1. Description of the reference dairy production systems by 2020. Data for Spanish dairy farms comes from Egas et al. (2020), whereas for Swedish dairy farms comes from Arla Foods (2022). Data for the annual water consumption per cow is obtained from Le Riche et al. (2017).

Item	Spanish dairy farms Mediterranean	Swedish dairy farms Northern
Average number of lactating cows (heads per farm)	50	102
Annual milk production (kg FPCM/cow)	8 154	9 422
Annual water consumption (drinking) (L/cow)	12 960	11 420
Grazing/pasture area per farm (ha)	50	208
Annual electricity consumption (kWh/cow)	337	1448
Fraction roughage in ration in the herd (%)	72	67
Number of milking per day	2	Between 2 and 3
Average annual temperature (°C)	13.3	6.6

Regarding the background data, the origin of the soybeans used in the Spanish case study is unknown, so this information was traced by using FABIO (see section 4.3.1). Similarly, the regional water supply mix was not reported for the two case studies so the WSmix model is used for 2020 and 2050 (see section 4.3.2.1).

4.3.1 Results from module 1

The current (2020) and future (2050 SSP2-4.5) climate variables (relative humidity, precipitation, and maximum and minimum temperature) for the two case studies are shown in Figure 4.2. Monthly climate normals are extracted from the World Bank Group (2021) and NASA (2021) and directly plotted. Then, these climatic data are used as inputs for the models on heat stress and cow diseases as well as for Aquacrop in module 2.

³ The reference inventories used were built on the former version of the IDF guidelines.

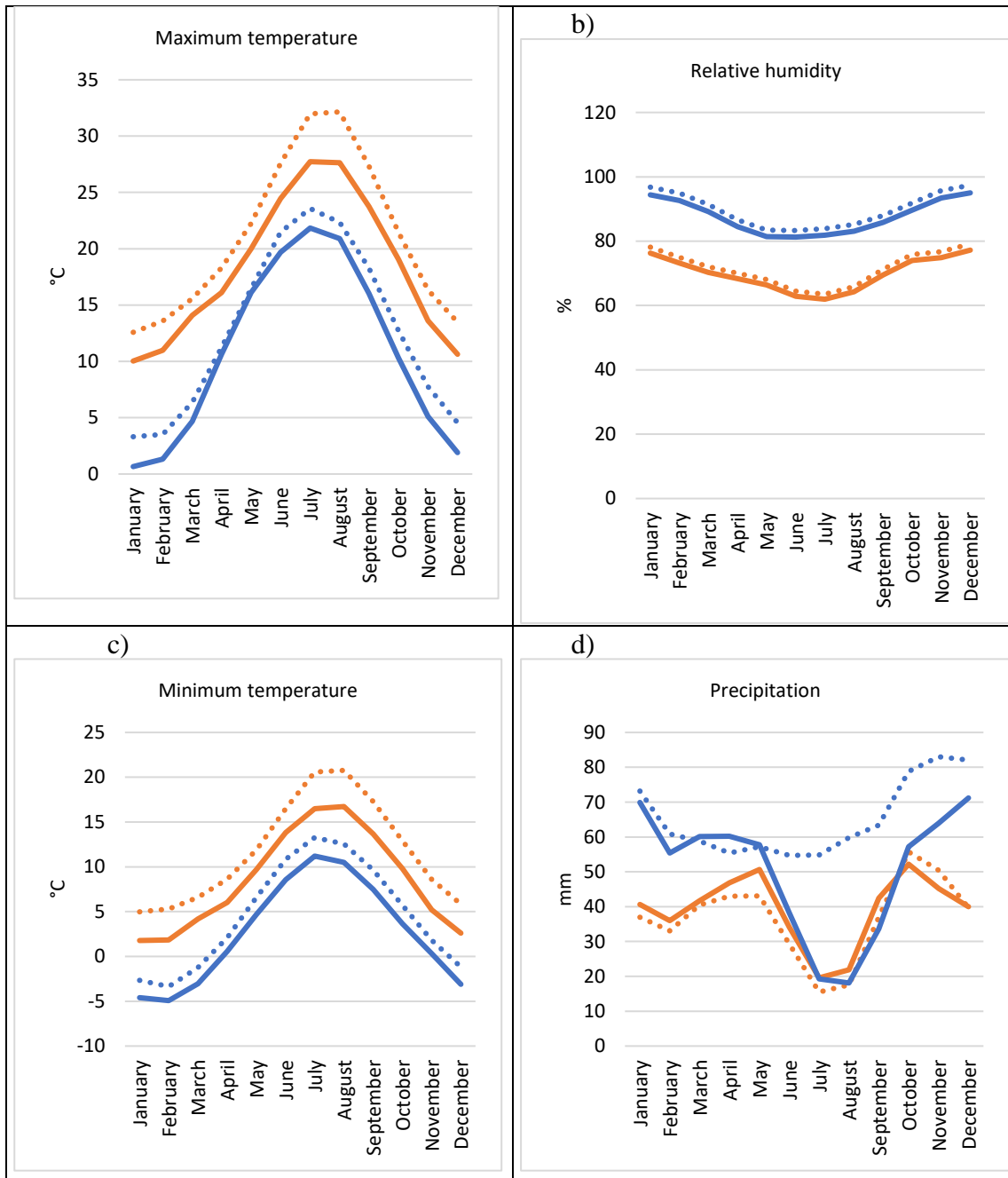


Figure 4.2. Orange colour represents the Spanish case study (Mediterranean region) and blue colour represents the Swedish case study (Northern region). The thick line is for the current (1991-2020) climatology and the dotted line is for the future (2040-2059) climatology under the SSP2-4.5 scenario.

As reported by Arla Foods (2022), the off-farm feed (i.e., soybeans) used by Swedish dairy farms come from Brazil. Nevertheless, this information was not available for the Spanish case study, and thus, FABIO is used. At present, available data (by 2013) has to be taken for both, current (i.e., 2020) and future (i.e., 2050) scenarios. This may be a limitation since crop provision is a global market that will be unevenly affected by climate change, and therefore, crops producing countries might not remain the same as latter discussed in section 4.4. Having said that, FABIO identified Brazil as soybeans origin.

4.3.2 Results from module 2

Taking as reference the LCIs obtained from literature for 2020 for both case studies, this section describes how module 2 can estimate the climate hazards and their biophysical impacts across the case study regions by 2050 under a SSP2-4.5 scenario. Climate hazards, their biophysical impacts, and their link to the LCIs and reference flows are described below for the two case studies. The obtained reference LCIs (i.e., 2020) and the resulting hypothetical LCIs for both case studies are collected (see Tables S1 and S2 in supplementary material of the resulting paper from this chapter).

4.3.2.1 Water stress

At the Northern region, the current regional water stress reached 11%, and it is expected to remain the same for the future (WRI, 2022). The current water supply mix relies on 51% of surface water and 49% of groundwater (Leão et al., 2019), share that will remain the same according to the projections done (Leão et al., 2019).

At the Mediterranean region, the current regional water stress is 64% and the future regional water stress will be 70% (WRI, 2022). The current regional water supply mix is composed of 80% surface water and 20% groundwater (WRI, 2022); and the future supply mix will decrease that sources to 71% from surface water and 15% from groundwater, and include then other sources: 10% from non-conventional water and 4% from external sources (Leão et al., 2019). Those new sources will imply additional electricity demand that have been taken into account as follows:

- Reverse osmosis is defined as the technology used for seawater desalination (i.e., non-conventional), with an electrical cost ranging from 3.3 to 5 kWh/m³ (Antonyan & Hoekstra, 2019).
- In the inter-basin water transfer (i.e., external sources), the water is transferred from long distances, and consequently, electricity increases in average 0.5 to 1.4 kWh/m³, where distances, elevation, pump efficiency and other factors are considered (Tow et al., 2021). Also, it can cause water stress in the region of water extraction, but it remains out of the scope of this chapter.

4.3.2.2 Floods

Floods, together with many other climate and non-climate hazards, lead to changes in the geographical distribution of crops and, consequently, transportation distances might change. Besides, crop-growing areas changes can also modify the environmental impact of raw milk since agroecological practices vary throughout countries. However, due to the lack of projections regarding the future distribution of crops as well as the future production systems, those variations cannot be estimated. As a conservative assumption, FABIO was used to define the crop origin by 2050, which, as already states (section 4.3.1 of this chapter), is a limitation of this study.

Having said that, this section instead identifies the occurrence of floods in both region of interest (Mediterranean and Northern) as well as in Brazil (i.e., off-farm feed origin).

Permanent floods were not identified in the Mediterranean Spanish side neither at the present nor at the future scenario. However, permanent floods were identified both in the Northern region and in Brazil. Permanent floods are identified only on the west coast of the Swedish case study for both temporal scenarios, and dairy farmers and respective croplands located in this area can be displaced by this climate hazard and suffer from saltwater intrusion.

Flash floods were identified across the two case study regions and Brazil. Currently, flash floods are already present and its occurrence is expected to rise for the future scenarios due to an increase in heavy winter precipitation (EEA, 2014). In the Northern region, flash floods will be mainly present in summer and winter, whereas in the Mediterranean region they will occur mostly in winter. Regarding Brazil, prolonged flash floods mainly in regions of the amazon are projected, which will be aggravated due to deforestation.

4.3.2.3 Crop pest infestation and climate variability

The current net yields of the on-farm and off-farm feedstuffs used in the two case studies are extracted from FAOSTAT (2022). Then, the future yield of off-farm feedstuffs is estimated based on the percentage of yield change, which is obtained from Hristov et al. (2020) for feedstuff grown in Spain and Sweden and from the IPCC (2022) for the ones grown in Brazil (Table 4.2).

Table 4.2. Changes in yields in a plausible scenario of the 5 crops used at the case study dairy farm.

	Crops	Crop origin	Yield change (%)
Spanish dairy farms in the Mediterranean	Barley	Spain	-7.1
	Wheat		-5.6
	Maize		-25.6
	Alfalfa		-18.2
	Soybeans	Brazil	-15.0
Swedish dairy farms in the northern	Grass	Sweden	+15.0
	Barley		+11.1
	Wheat		+16.7
	Oats		+11.1
	Rapeseed		+16.7
	Maize		+19.7
	Beans and peas		+12.7
	Fodder beet		+16.7
	Soybeans	Brazil	-15.0

4.3.2.4 Heat stress

An increase in raw milk losses is associated to a modification of the reference flows. Thus, using climate data from Module 1 in Equations 1 and 2, it is possible to estimate the number of months during which cows experience heat stress and the corresponding raw milk losses for both case studies in the SSP2-4.5 scenario is possible.

Currently, Spanish dairy cows in the Mediterranean face an average 4 months of heat stress, resulting in 1.6% of annual raw milk losses. As the reference flow for the reference scenario already considers this never-produced raw milk, the reference flow remained the same (1.0 kg of FPCM). However, when climate conditions by 2050 under the SSP2-4.5 scenario are considered, the average number of months experiencing rises to 6. As a result, annual raw milk losses rise to 3.7% despite the increase in milk yield due to on-farm improvements. When no on-farm improvements are considered, annual raw milk losses rise to 5.6%.

Similarly, under current climate conditions, Swedish dairy farms in the northern encounter 2 months of heat stress, leading to 0.03% of annual raw milk losses in a reference scenario. Nevertheless, heat stress events increase to 3 months for the SSP2-4.5 scenario, and this leads to 0.2% of annual raw milk losses when on-farm improvements are taken. Raw milk losses rise to 0.3% when no improvements are considered.

4.3.2.5 Cow diseases

By using the model framework from Guzmán-Luna et al. (2022), the annual raw milk losses caused by mastitis from *S. aureus* are estimated for both case studies for the future scenario. Similar as heat stress, the reference flow for the reference scenario already accounts for raw milk losses from cow mastitis, and thus, it remains as 1.0 kg of FPCM.

Under current climate conditions, a total of 2.0% of annual raw milk losses are estimated across Spanish dairy farms in the Mediterranean. Under future climate conditions (i.e., scenario SSP2-4.5), annual raw milk losses reach 1.5% when on-farm improvements are implemented; however, they increase to 2.2% when on-farm improvements are not considered.

Across the Swedish dairy farms in the northern and under current climate conditions, annual raw milk losses reached 1.2%. In a future scenario (i.e., SSP2-4.5), dairy farms across this region presented 0.9% of raw milk losses when assuming on-farm improvements. The percentage of raw milk lost increased to 1.4% when no on-farm improvements are implemented.

When the percentage losses from cow diseases and heat stress are put together, it results in 5.2% and 1.1% of raw milk losses on the dairy farm in the Mediterranean and Northern region, respectively, if on-farm improvements are considered. In both cases, reference flow increases to 1.054 and 1.011 kg of FPCM, respectively. However, these percentages increase up to 7.8% and 1.7% when on-farm improvements are not implemented. As a result, the reference flow for the dairy farm in the Mediterranean rise to 1.084 and the reference flow for the case study in the Northern region increase to 1.0173 kg of FPCM.

4.3.3 Results from module 3

Once the percentage changes in the two LCIs calculated with the previous module were incorporated (see Table S1 and S2 in supplementary material of the resultant paper from this chapter), the life cycle impact assessment was carried out followed by the contribution analysis. They showed that across the Spanish case study, the GW per FU increases by 5.5% (i.e., 0.054 kg CO₂e), the WU by 5.4% (i.e., 0.006 m³), and the LU by 16.0% (i.e., 0.086 m²) from the reference to the future scenario when on-farm improvements are considered (Figure 4.3). The reference flow by 2050 with on-farm improvements is 1.054 kg of FPCM because of raw milk losses (i.e., cow heat stress and diseases). For GW and WU, raw milk losses from heat stress and mastitis are the main contributor to this rise, being responsible for 5.2%.

The increment in the environmental impact per FU remains unequal across regions. Across the Swedish case study, the GW rose by 1.1% (i.e., 0.01 kg CO₂e), the WU increased by 1.1% (i.e., 0.000041 m³), and the LU by 1.0% (i.e., 0.0001 m²) from current to future climate conditions with on-farm improvements (Figure 4.3). In this case, the reference flow by 2050 increase to 1.011 kg of FPCM due to raw milk losses (i.e., cow heat stress and diseases).

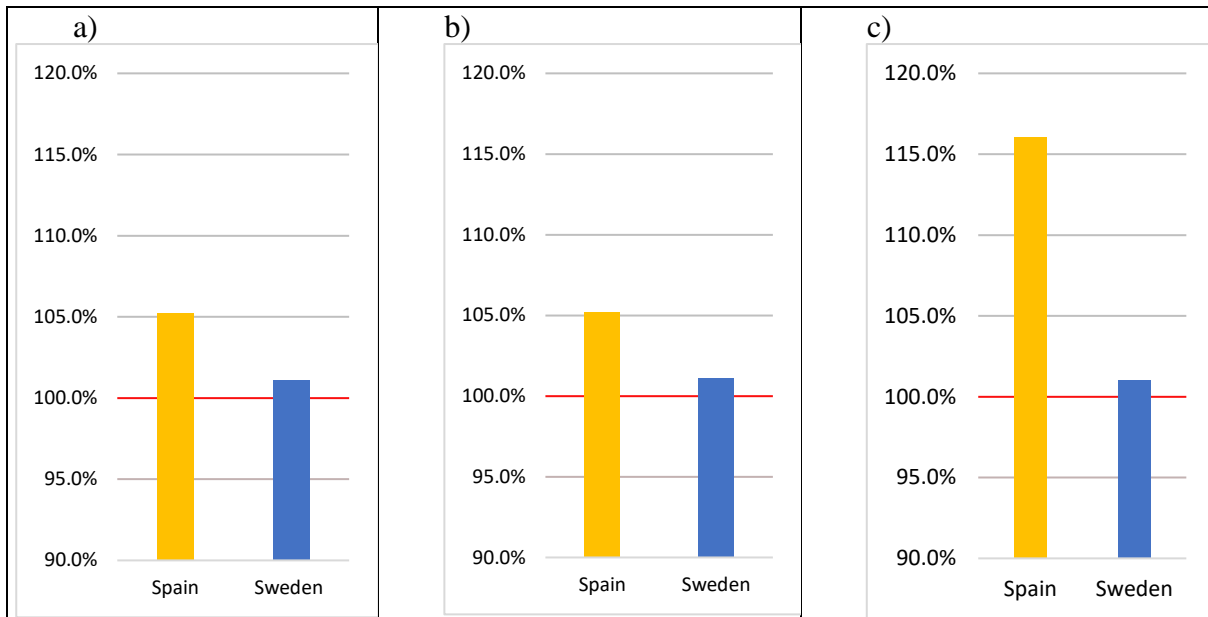


Figure 4.3. Percentage increase of the global warming (a), water depletion (b), and land use (c) of 1 kg of FCPM produced across Spanish dairy farms located in the Mediterranean and Swedish dairy farms in the northern region from 2020 to 2050. Red line shows the reference value by 2020 (Vertical axis start at 90%).

4.4 LIMITATIONS

Despite the uncertainty and complexity involved (interconnections, non-climate hazards, lack of information and computational requirements), this chapter proposes a toolbox that provides an in-depth understanding of climate hazards and their biophysical impacts at dairy farm level. But this chapter recognizes the limitations of the toolbox.

The first limitation lies in the uncertainty propagation from three sources (i.e., data sources, climate scenarios, and natural climate variability).

The first source relates to the used data sources. Concerning data sources, authors of Aqueduct 3.0 recognize the presence of uncertainty, as in any other future projection, and no uncertainty assessment is provided. This uncertainty was propagated to the results from the water supply mix model as it was built on Aqueduct 3.0. Another used data source is FABIO. However, it is built on FAO data, which presents uncertainty that might affect the commodity balances within the IO table. Finally, climate data is obtained from CMIP6, which is the most common climate model used. Even though this model represents significant improvements over its previous generations, uncertainty is still present.

The second source is linked to the climate scenarios (i.e., SSPs and RCPs). There is no complete knowledge about the socio-economic and technological developments in the future. Unknown unknowns are present, and they are not captured in the scenarios. Despite this, the RCPs and SSPs are made to span the range of possible scenarios instead of to predict them.

The third source of uncertainty is linked to natural climate variability that influences the used climate data. Natural climate variability refers to the temporal variation of the climate system due to natural processes. They are unpredictable natural fluctuations that occur even without any change in the GHG concentrations. It can affect the climate models that produce the projected climate data used in this chapter. Among the three sources, data sources present the largest impact on the results and climate scenarios is the second one (Lehner et al., 2020).

The second limitation lies in the assumptions made in view of the lack of information. For instance, no projected input-output table or projected land use maps were found to identify the global market of crop provision by 2050, and thus, FABIO for 2013 was still used. It is recognized as a conservative approach since countries of provision may change in the future due to the effects of climate change and other non-climate factors, and as a result, incorrect countries of provision might be defined with data from 2013. The importance of identifying the correct origin of the off-farm crops is that changes in the crop yield will differ across regions due to the uneven impacts of climate change. Whereas in one country the yield of a certain crop will increase by 2050, in another country the yield of the same crop will decrease. Therefore, incorrect identification of the countries of crop provision can lead to an inaccurate assessment of Module 2, being reflected mainly in the results on land use (LU) from Figure 4.3.

Also, this chapter is limited to changes of the LCI caused by climate change, but the impacts of this global issue might also affect the LCIA. For instance, characterisation factors are dependent on site-specific conditions that are affected by climate change. However, it is not covered under the scope of the present chapter.

4.5 CONCLUSIONS

Clearly, climate hazards will pose biophysical hazards to European dairy farms by 2050, resulting in changes in their environmental performance across regions. Thus, the European dairy sector will face more challenges in achieving its environmental targets. Changes in the environmental performance will occur unevenly across regions, negatively impacting the Mediterranean region of Europe. From a GW and WU standpoint, the rise in dairy farms' environmental impact is primarily attributable to raw milk losses. However, from the perspective of LU, crop pest infestation and climate variability are the two primary climate hazards.

This chapter does not seek to report a robust estimate of how much the environmental performance of European dairy farms will change in 2050; rather, it proposes a toolbox for evaluating the future impacts of climate change on European dairy farms and estimating changes in the LCI in a complex and uncertain landscape. The toolbox can generically be used in different biogeographical regions and temporal windows. The deployment of the toolbox permits the exploration and identification of potential future scenarios for European dairy farmers.

This toolbox can assist the dairy sector, particularly dairy farmers, in identifying the climate hazards they will face in the future. This study is a steppingstone in enabling the dairy sector's decision-making to begin building adaptative capacity immediately to reduce its vulnerability to climate change in the future.

5. EVALUATION OF SITE-SPECIFIC ADAPTATION STRATEGIES

SUMMARY

The unavoidable climate hazards and their biophysical impacts are expected to challenge unequally European dairy farms by 2050. In this sense, adaptation strategies are necessary; however, they require material and resource usage during their operation, influencing the environmental performance of dairy farms.

This chapter implements a step-by-step framework to identify site-specific adaptation strategies capable to adjust to local climate hazards. Then, an evaluation to identify potential win-win adaptation strategies is done, which are those whose environmental impact is offset by the avoided biophysical hazards. Here two case studies are selected as they present contrasting climate conditions: a dairy farm in the Mediterranean region of Europe and a dairy farm in the Northern region of Europe by 2050 under the SSP2-4.5 climate scenario. From the analysed strategies, the implementation of heat abatement systems resulted in a win-win adaptation strategy as they guaranteed food safety and avoid raw milk losses. So, the net environmental cost of this strategy is completely offset by the avoidance of these losses.

The content of this chapter is built from a manuscript to be submitted to the Sustainable Production and Consumption journal:

- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2023). Evaluating win-win site-specific dairy farm adaptation strategies to climate change by 2050. *Journal of Sustainable Production and Consumption* (To be submitted).

5.1 INTRODUCTION

The European Green Deal is pushing and motivating sectors, including the dairy sector, to align to its environmental and climate ambitions by 2050 in which carbon neutrality is part of the agenda (EDA, 2019). However, reaching this ambition is not exempt from challenges due to the existing interaction between the environmental impact of the dairy sector and the effects of climate change on its environmental performance (Guzmán-Luna et al., 2021). This sector has significantly reduced its greenhouse gas (GHG) emissions per kilogram of fat protein and corrected milk (FPCM) in Europe, achieving one of the lowest carbon footprints in the world, and reaching an average of 1.5 kg of CO₂e (EDA, 2018b). In addition to global warming, this sector is also responsible for other environmental impacts linked to land use, freshwater use, and eutrophication (EDA, 2018; PCR, 2013).

Climate change is an ongoing phenomenon that is already having significant impacts on European dairy farms with regional differences (Figure 5.1). As a result of climate change, climate hazards will cause biophysical impacts along the dairy value chains, affecting their performance and food safety and contributing to climate change and other environmental impacts (Guzmán-Luna et al., 2023a). Along the value chain, the primary production stage is the most vulnerable one, as climate hazards and their biophysical impacts might directly affect crops and raw milk production. So, water stress is likely to lead to crop yield reductions and changes in the regional water supply mix, and floodings might change crop geographical distribution. Besides, crop pest infestation and climate variability can also change the distribution of crops and reduce their yields in certain regions of the world. Other potential climate hazards also include cow heat stress and cow diseases, such as bovine mastitis, that lead to an alteration of the cows' milk yield and quality (e.g., microbial and somatic cell count related) due to the presence of food safety risks and spoilage, increasing the raw milk losses (Guzmán-Luna et al., 2021). On top of this, climate change is projected to generate favorable conditions for exacerbating the spread of chemical and microbial hazards at the dairy farm, leading to an increase of raw milk losses as the European regulatory limits for somatic cell count (SCC) and microbial load are expected to be exceeded (Guzmán-Luna et al., 2022).

As a response of climate hazards and their biophysical impacts, adaptation strategies¹ are required to avoid or compensate for them (Figure 5.1). However, they are less explored compared to mitigation strategies², which have been very well investigated and numerous strategies have been put in place to improve the environmental performance of the dairy sector (Boadi et al., 2004; Van Middelaar et al., 2013).

Adaptation strategies need material and energy resources for operating and may also release emissions, and therefore, the environmental performance of the system might be affected. But the environmental cost of the adaptation strategy might be balanced as certain strategies might affect the amount of milk produced and ready to be sent to the factory. So, the net environmental cost of certain strategies might be reduced or even offset.

¹ Adaptation strategies look at adjusting and minimizing the negative effects of climate change and seizing on potential opportunities (IPCC, 2022).

² Mitigation strategies seek reducing the contribution to climate change (IPCC, 2022), and they include carbon sequestration, improvement of diets to reduce enteric fermentation, and efficient use of fertilizers to mention some (Rojas-Downing et al., 2017).

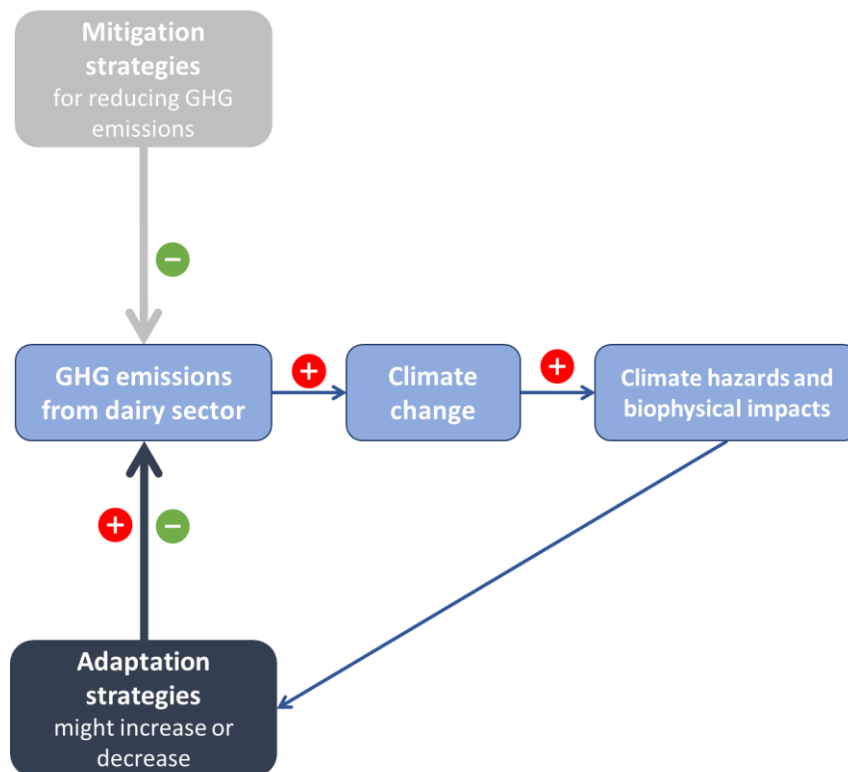


Figure 5.1 Interactions between climate change, changes in dairy sector performance, and adaptation/mitigation strategies.

To assist the European dairy sector in this challenging path towards its reaching given ambitions and reinforce adaptation to climate change of primary production, this chapter aims to estimate the net environmental cost of adaptation strategies to be able to identify win-win strategies, i.e., those able to adapt the dairy farm activities to the site-specific climate hazards but doing so at the minimal environmental cost and guaranteeing the compliance of food safety requirements. Section 5.2 describes the framework followed to identify suitable adaptation strategies likely to be implemented into two case studies with contrasting climate conditions (i.e., Mediterranean and Northern of Europe) as well as to identify win-win adaptation strategies based on their net environmental cost. Section 5.3 shows the identified site-specific adaptation strategies and collects the available methods to quantify their net cost. In this section, potential win-win strategies are then described. Section 5.4 highlights the importance of integrating methodologies for evaluating adaptation strategies and designing win-win solutions. Finally, section 5.5 provides conclusions in which the contribution of this chapter to the dairy sector is described.

5.2 METHODS: FRAMEWORK FOR WIN-WIN SITE-SPECIFIC ADAPTATION STRATEGIES

A framework is defined and followed in this chapter to evaluate adaptation strategies and identify win-win site-specific adaptation strategies. Such framework is composed of five steps (Figure 5.2):

- 1) Preparation of the ground for adaptation in geographical and temporal-climatic terms, as further described in section 5.2.1.
- 2) Identification and understanding of the site-specific climate hazards and their biophysical impacts to be tackled across the geographical horizon defined previously.

This step is built on the in-depth analysis based on Guzmán-Luna et al. (2023) as detailed in section 5.2.2.

- 3) Black and grey literature review to identify generic adaptation strategies to address the identified climate hazards at the dairy farm level (i.e., water stress, floods, crop pest infestation, climate variability, cow heat stress, and cow diseases), as further described in section 5.2.3.
- 4) Selection of site-specific adaptation strategies for each case study as well as identification of methods to evaluate them as detailed in section 5.2.4.
- 5) Evaluation of the net environmental cost (or benefit) of the site-specific adaptation strategies, which will be the criteria to identify win-win adaptation strategies (section 5.2.5).

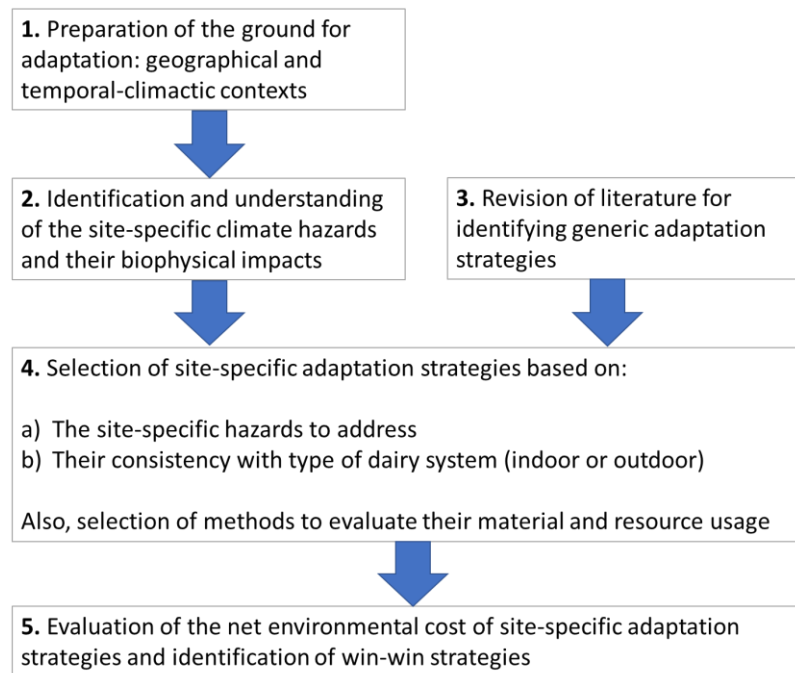


Figure 5.2. Framework for identifying win-win site-specific adaptation strategies.

5.2.1 Preparation of the ground for adaptation: geographical and temporal-climatic contexts

Across Europe, dairy farms are concentrated in four biogeographical regions (i.e., Mediterranean, Continental, Northern, and Atlantic). Among the four regions, the Mediterranean is the most vulnerable to rising temperatures and extreme weather events, such as heatwaves, droughts, and wildfires (EEA, 2017).

There is evidence that these changes will have negative impacts on agriculture, including dairy farms and crop production (EEA, 2019). This region is also anticipated to experience significant impacts on freshwater availability, which is an essential resource for agricultural use. In addition, a higher spread of disease vectors is forecasted for this region, affecting dairy farms and croplands (EEA, 2017, 2019; IPCC, 2022) Across this region, bovine mastitis prevalence is expected to increase as well as the number of cow heat stress events, leading to a rise of raw milk losses (Guzmán-Luna et al., 2023a).

Differently, the Northern region is expected to experience heavy precipitation events that will trigger flash floodings, making croplands unsuitable. But also, permanent floods, due to

sea level rise, and warmer temperatures are expected for this region. As a result, crop yields of certain crops are projected to increase, mainly due to the availability of water since no risk of water stress is expected there (EEA, 2017, 2019). However, warmer temperatures can have negative effects as pathogen growth is expected to benefit from it, leading to higher bovine mastitis prevalence, and thus, higher raw milk losses (Guzmán-Luna et al., 2022). And also cow heat stress events are expected to increase, leading to a rise in raw milk losses but to a lesser extent compared to the Mediterranean (Guzmán-Luna et al., 2023a).

So, to account for two different geographical contexts, a dairy farm located in the Mediterranean and another located in the Northern region are selected. Besides and to cover more potential adaptation strategies, the Mediterranean farm is assumed to be indoor system, whereas the Northern one is an outdoor system.

The climate conditions that the two case studies will face by 2050 will vary depending on the scenario used (IPCC, 2022). The one selected here has been the SSP2-4.5 since it is recognized as a plausible climate scenario, which is characterized for a global average temperature increment of 1.4°C by 2050 (IPCC, 2022).

5.2.2 Identification of the site-specific climate hazards and their biophysical impacts

Climate hazards and their biophysical impacts remain unequal depending on the region and climate scenario analyzed, so its site-dependent identification and evaluation is an essential step to choose the most appropriate one(s) in each case study.

A climate change impact assessment (CCIA) is recommended by FAO (2007) to identify and evaluate given climate hazards and their impacts. In general, CCIA includes climate impact chains (ClimateADAPT, 2023; Kondrup et al., 2022). On the one hand, the climate impact chains allow the identification and understanding of the causal relationships between climate hazards (i.e., cause) and their impacts (i.e., effects) on different sectors. On the other hand, they serve as a backbone for the identification and integration of different data sources (e.g., simulation models, tools, software, and literature) to be able to quantify climate hazards and their effects. Guzmán-Luna et al. (2023) carried out an assessment on the impacts of climate change on the European dairy sector and developed a toolbox able to estimate climate hazards and their biophysical impacts on dairy farms (Figure 5.3) across regions and climate scenarios. The application of such toolbox on the two case studies defined here leads to the identification of the site-specific climate hazards present at the dairy farm level in the Mediterranean and the Northern region of Europe under the selected SSP2-4.5 scenario (Figure 5.4).

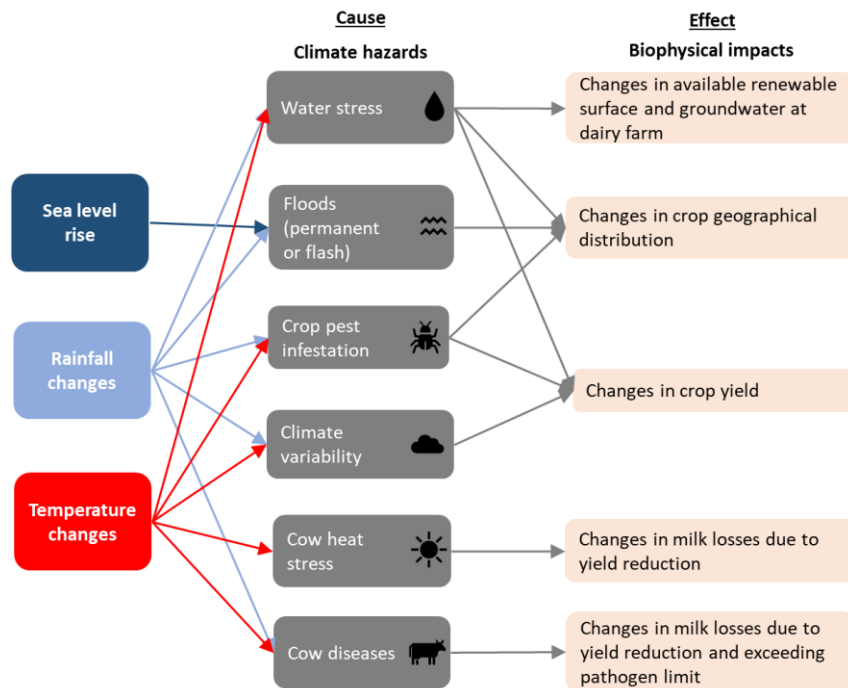


Figure 5.3. Climate impact chain for dairy farms adapted from Guzmán-Luna et al. (2023).

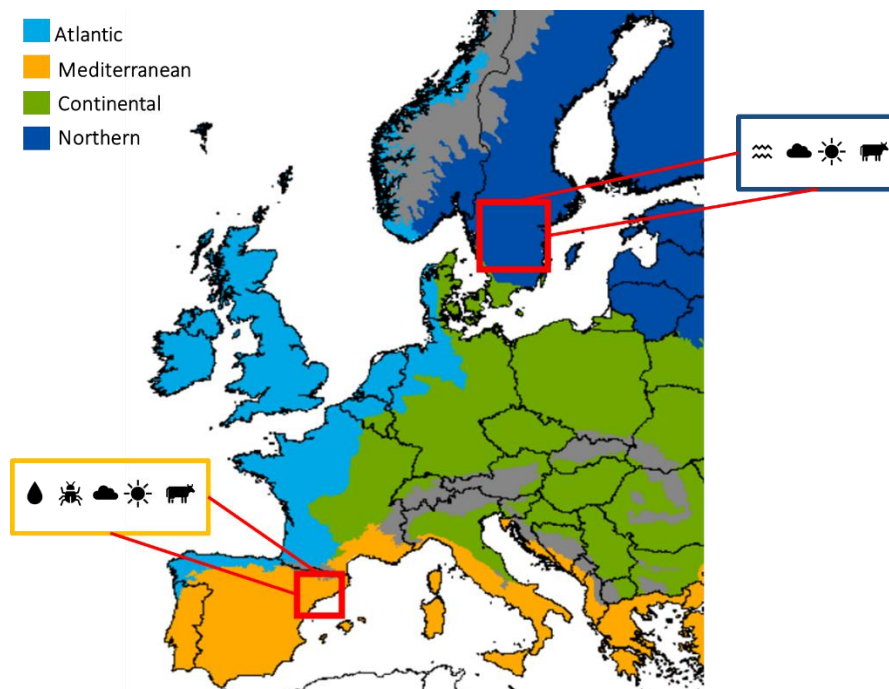


Figure 5.4. Climate hazards identified across the two case studies by 2050 under the SSP2-4.5 scenario.

5.2.3 Revision of literature for identifying generic adaptation strategies

Black and grey literature were revised (Table 5.1) to build a collection of potential adaptation strategies to be implemented at the dairy farm level (Table 5.2). The literature review also included documents covering countries outside Europe since these countries are already dealing with certain climate hazards projected for Europe in 2050. Certain adaptation strategies address more than one climate hazard and some of the strategies were found in more than one

documents. However, in any of the documents, an evaluation of the net environmental cost of adaptation strategies was carried out.



Table 5.1. Literature revised to define the portfolio of potential adaptation strategies.













Name of the document	Source	Coverage	Type ⁽¹⁾
Sustainable adaptaiton of typical EU farming systems to climate change	(AgriAdapt, 2017)	Europe	R
Climate change-related risks and adaptation strategies as perceived in dairy cattle farming systems in Tunisia	(Amamou et al., 2018)	Tunisia	P
CLIMALAIT: Adapting to climate change for resilient French dairy farms	(Climalait, 2021)	France	R
Vulnerability and adaptation strategies of dairy farming systems to extreme climate events in southwest Uganda	(De Vries, 2018)	Uganda	R
An EU Strategy on adaptation to climate change	(EC, 2013)	Europe	R
Climate change, impacts and vulnerability in Europe 2016	(EEA, 2017)	Europe	R
Climate change adaptation in the agriculture sector in Europe	(EEA, 2019)	Europe	R
Analysis of climate change impacts on EU agriculture by 2050	(Hristov et al., 2020)	Europe	R
Adaptation strategies of cattle farmers in the dry and sub-humid tropical zones of Benin in the context of climate change	(Idrissou et al., 2020)	Benin	P
Climate Change 2022: Impacts, Adaptation and Vulnerability	(IPCC, 2022)	Global	R
An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system	(Kalaugher et al., 2013)	New Zealand	P
Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: A case study of Chagaka Village, Chikhwawa, Southern Malawi	(Nkomwa et al., 2014)	Malawi	P
OptiBarn - Optimised animal specific barn climatization facing temperature rise and increased climate variability	(Optibarn, 2017)	Europe	R
Climate change and livestock: Impacts, adaptation, and mitigation	(Rojas-Downing et al., 2017)	Global	P

⁽¹⁾ P = scientific paper, R = report

From the 14 identified adaptation strategies (Table 5.2), certain strategies are specifically suited to indoor systems, where cows have restricted or limited access to grazing, while others are more appropriate for outdoor systems, where cows have access to open grazing. That is the case of AD03 or AD11. Also, certain strategies require of suitable climatic conditions to be successful. For instance, dams or valley tanks are not feasible in regions without rain.

Table 5.2. Generic adaptation strategies from literature.

Code	Adaptation strategy	Description	Dairy system ⁽¹⁾	Addressed climate hazard ⁽²⁾
AD01	Cooling systems	Cooling systems depends on fans and/or sprinklers and they are activated when the temperature-humidity index exceeds the dairy cow threshold	I	
AD02	Resilient breeds	Dairy farmers have access to genetically improved breeds resistant to heat and mastitis as a response of genetic approaches (i.e.,	Both	

		selective breeding, genomic selection, and gene editing)		
AD03	Provision of shade	It is a mechanism to lessen the physiologic response of dairy cows to heat stress. A shade structure made of materials, such as metal or wood, is installed to cover open grazing areas	O	
AD04	Shifting of locations of on-farm crop production	It is an option when on-farm crop production is not possible due to climate hazards. This involves relocating on-farm crop production to areas where the pressure of crop pest, climate variability and water stress is non-existing	I	
AD05	Migration of dairy herd	Displacement of the dairy herd to another site where they have access to water	O	
AD06	New treatment interventions	The implementation of bacteriophages is a promising intervention for cow mastitis	Both	
AD07	Ecosystem-based approaches (EbA)	EbAs incorporates ecosystem services and biodiversity. Agroforestry is an example of it, which integrates trees (e.g., timber or fruit trees) or into the grazing land and/or crop fields	Both	
AD08	Resilient crops	Dairy farmers adopt genetically improved crops resilient to floods, droughts, changing climatic conditions, and crop pests	Both	
AD09	Inter-basin water ferrying	Transporting water from another basin. In this chapter, it is assumed that water is transferred from the nearest basin without water stress	Both	
AD10	Dams or valley tanks	Construction of dams or tanks to store large amounts of rainwater. This is only possible in regions with high precipitation	Both	
AD11	From grazing to indoor	Restrict grazing during very wet periods	O	
AD12	Alternative feeds	Incorporation of alternative feeds, such as microalgae or insects	Both	
AD13	Dig trenches	The construction of dig trenches for drainage and direct water flow	Both	
AD14	Fenced perimeter	The perimeter of dairy farms is protected by short concrete walls	Both	

⁽¹⁾ I = indoor system, O = outdoor system // ⁽²⁾ Icons definition can be found in Figure 5.3

5.2.4 Selection of site-specific adaptation strategies and methods

Considering the site-specific climate hazards to be addressed (Figure 5.4) and the type of dairy farm system implemented, the adaptation strategies collected in Table 5.2 were filtered and a selection of the most suitable ones for the two case studies was done (Figure 5.5). Adaptation strategies were selected based on the identified site-specific climate hazards from Figure 5.4 that need to be addressed.

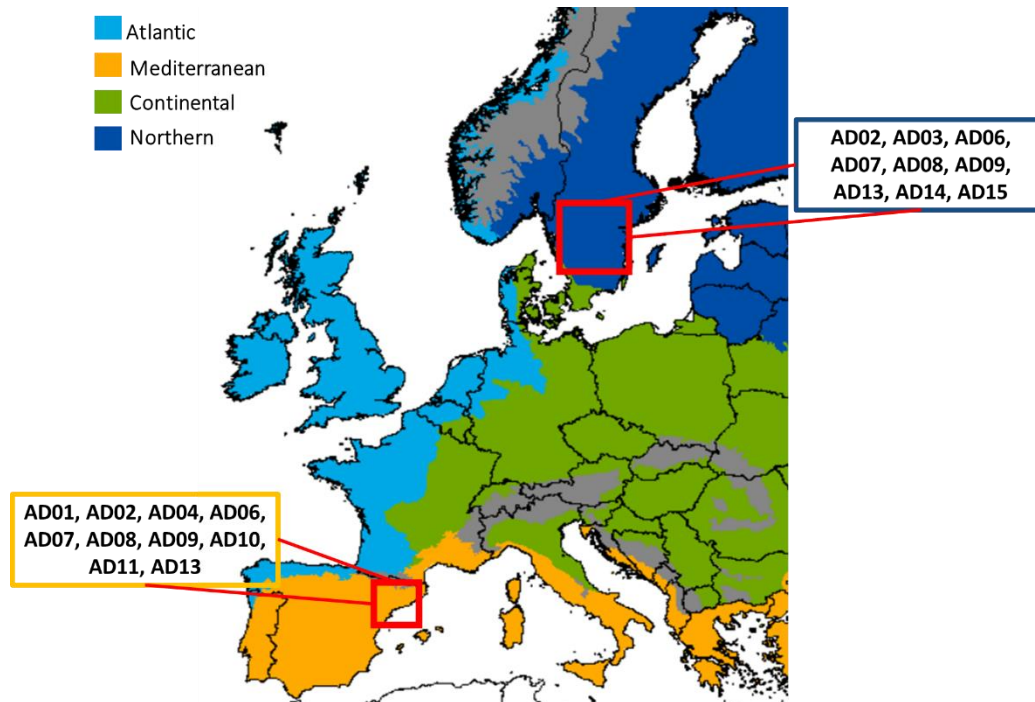


Figure 5.5. Adaptation strategies for each case study (the numbering corresponds to the codes given in Table 5.2).

5.2.5 Evaluation of net environmental cost to identify win-win adaptation strategies

Once the selection of the suitable adaptation strategies has been done, a quantification of the material and energy resource usage associated with each implementation is needed to account for the additional environmental cost related to it. Also, the expected benefits of the selected adaptation strategies need to be quantified, so the net environmental cost (For details on the intermediate calculations, see supplementary material of the resulting paper of this chapter) is obtained:

A win-win strategy will be the one able to balance its additional environmental cost with the benefits in terms of product obtained (stated as 1 kg of FPCM). So, the impact caused in terms of units of the environmental indication per unit of raw milk produced is lower than the impact caused before implementing the adaptation strategy.

A -win-win strategy will be the one that its additional environmental cost is not offset by the benefit provided. So, the impact caused in terms of units of the environmental indication per unit of raw milk produced is higher than the impact caused before implementing the adaptation strategy.

Three life cycle-based indicators have been identified as relevant for dairy farming (Huijbregts et al., 2017):

Global Warming (GW) measures the potential of substance to contribute to global warming and it is expressed in terms of the equivalent amount of carbon dioxide (CO₂) emissions over a specified time horizon.

Water Use (WU) determines the amount of water consumed by a product or service and it is commonly measured in m³. It is based on the water scarcity concept that considers the water consumed or withdrawn in a specific area during a year.

Land Use (LU) refers to land occupation or transformed during a period for agricultural purposes as it damages the ecosystem and its services. It is expressed as m² per year.

For the quantification on the three indicators the impact assessment method ReCiPe Midpoint (H) v1.13 (Huijbregts et al., 2017) has been used. Their joint evaluation makes more clear their strong interconnection, i.e., the called Water-Energy-Food-Ecosystem (WEFE) nexus (Carmona-Moreno et al., 2019) which highlights the interdependence of water, energy (strongly linked to GHG emissions) and food security and ecosystems – water, soil, and land – that underpin that security, and also provides an informed and transparent framework for determining the proper trade-offs and synergies that maintain the integrity and sustainability of ecosystems.

To evaluate the baseline environmental performance (i.e., before any adaptation strategy enters into play and considering the effects of climate change) and the adapted one (i.e., after the implementation of the selected adaptation strategies), two inventories were constructed based on Egas et al. (2020) and Arla Foods (2022)³ to represent the Mediterranean and Northern case studies, respectively. Based on them, the baseline environmental performance for both case studies were calculated using Activity Browser v2.7.5 (Steubing, 2015), obtaining the following values (see first tab in supplementary material from the resulting publication of this chapter for details):

Mediterranean dairy farm:

$$GW = 1.058 \text{ kg CO}_2\text{eq} / \text{kg FPCM}$$

$$WU = 0.119 \text{ m}^3\text{eq} / \text{kg FPCM}$$

$$LU = 0.630 \text{ m}^2 \text{ per year} / \text{kg FPCM}$$

Northern dairy farm:

$$GW = 1.008 \text{ kg CO}_2\text{eq} / \text{kg FPCM}$$

$$WU = 0.012 \text{ m}^3\text{eq} / \text{kg FPCM}$$

$$LU = 0.003 \text{ m}^2 \text{ per year} / \text{kg FPCM}$$

5.3 RESULTS AND DISCUSSION

Methods and data sources used to estimate the material and energy usage of the identified site-specific adaptation strategies are described below (quantitatively when possible, in section 5.3.1 and qualitatively in 5.3.2), as well as the resulting net environmental cost of given strategies is shown and discussed in section 5.3.3.

5.3.1 Quantifiable adaptation strategies

5.3.1.1 Cooling systems (AD01)

On-farm heat abatement systems are needed for indoor farms, which comprise fans and sprinklers to relieve cow heat stress and avoid raw milk losses. AD01 consumes then water and electricity, leading to an annual percentage increase in these two resources and a change in the environmental cost per amount of raw milk produced. Available equations are implemented to

³ Data not shown due to confidentiality issues.

estimate the amount of water and electricity required during heat stress months in a year. To do so, the number of months in which cows are under heat stress in a specific region and climate scenario is needed, and this was possible to be estimated with the toolbox from Guzmán-Luna et al. (2023). Then, the extra water used in the heat abatement system is estimated with equation 1 from Le Riche et al. (2017). Heat stress also leads to an increase in the cow's water intake, also leading to an annual percentage increase in water. Thus, equation 2 from Le Riche et al. (2017) is also used.

$$Spri_{annual} = \sum_{i=1}^n \frac{658.78 + (Tmax_{month,i}) - 11250}{500} \times 30 \quad (1)$$

$$Drink_{annual} = \sum_{i=1}^n 0.636 \times (Tmax_{month,i}) + 27.03 \times 30 \quad (2)$$

Where: $Spri_{annual}$ is the annual water demand of the sprinkler system (L/cow) and $Drink_{annual}$ is the annual water intake (L/cow) based on the maximum temperature ($Tmax_{month,i}$) (C°) of the specific months when cows are under heat stress annually.

Later, the extra electricity required in the heat abatement system is estimated with equation 3 from Herzog et al. (2021) similarly based on the maximum temperature of the heat stress month.

$$Ele_{monthly} = \left(\frac{\left(\left(\frac{Vent_{intensity} \times run_{time}}{1000} \right) \times power\ to\ mass\ ratio \right)}{1000} \right) \quad (3)$$

+ energy demand fan controller

Where: $Vent_{intensity}$ is the ventilation intensity, which is set at 870 $m^3/cow/h$ according to Herzog et al. (2021). Then, run_{time} refers to the fan operation time, which is obtained based on the number of months under heat stress estimated by Guzmán-Luna et al. (2023). The $power\ to\ mass\ ratio$ is set at 16.43 Wh/1 000 m^3 as defined by Herzog et al. (2021).

From the baseline inventories, it is known that a dairy cow in the Mediterranean requires 12 960 L per year. However, cow heat stress months are expected to increase from 4 to 5 across this region of Europe (Guzmán-Luna et al., 2023a). After the aforementioned three equations, it is estimated an increase of 44% of water and 28% of electricity. Later, these percentage increments are incorporated into the inventory created specifically for this adaptation strategy for the Mediterranean case study. Future electricity mix and water supply mix also needs to be considered, and they can be defined with the results from the model (i.e., WS-mix) developed by Leão et al. (2019). In that model, they carried out regionalized projections of water sources mix, technology, and associated electricity mix, which are the three main components of the water supply mix, for different users (e.g., public water, industry, and agriculture).

5.3.1.2 Provision of shade (AD03)

The construction of a structure to provide shade is commonly built with materials such as wood or metal. In the present chapter, the environmental cost of shading structures is not considered as it requires minimum materials with a long-life span. So, the environmental cost

of shading structures is then related to its land occupation. The size of the structure is then estimated based on the number of cows. According to the literature, it is recommended that a dairy cow occupies between 3.5 and 5.6 m² of shade (Schütz et al., 2010). This adaptation strategy is only required in the Northern of Europe, and the dairy farm under study has in average 102 lactating cows (Arla Foods, 2022b).

5.3.1.3 Shifting of locations for on-farm crop production (AD04)

Climate hazards projected in the Mediterranean region leads to a shift of the on-farm crop production towards areas where crop pest, climate variability and water stress pressure is lower. In the present chapter, the barley, maize, wheat, and alfalfa grown at the dairy farm under study (Egas et al., 2020) are assumed to be grown in the Northern region of Sweden as it is a region that do not present pressure of crop pest and water stress. Climate variability is expected across this region, but it will result in a positive impact (EEA, 2019). For instance, in northern regions of Europe, crop yield is expected to be benefit mainly due to warmer temperatures, the availability of water and the higher levels of CO₂ in the atmosphere. On the contrary, southern regions of Europe (i.e., Mediterranean) will experience crop yield reductions, despite the increment of CO₂ levels in the atmosphere, mainly due to water stress (EEA, 2019). In this context, a modification on the geographical distribution of crop can lead to changes in the transportation distances and it might lead to environmental costs.

5.3.1.4 New veterinarian treatment interventions (AD06)

Increased raw milk losses due to a rise in the pathogen mastitis prevalence is also projected for the two case study dairy farms as demonstrated by Guzmán-Luna et al. (2022). To avoid given increase in raw milk losses, new treatment interventions that includes the use of bacteriophages is promising. Bacteriophages are viruses that infect and kill bacteria without any negative effect on cows. The use of them can be efficacy for the treatment of bovine mastitis caused by the major pathogens that include *Staphylococcus aureus* and *Escherichia coli* (Breyne et al., 2017; Guo et al., 2021). The use of bacteriophages can be an alternative to treat the increasing prevalence of mastitis (Gutiérrez et al., 2019). The bacteriophage is commonly diluted in water in which 18L of water are required per every 20L of phage used. In the present chapter, it is assumed that this type of mastitis treatment is produced in the Netherlands (Feliciano et al., 2023). Thus, the production of the bacteriophages, the transport of them to the two dairy farms under study and the water required for their dilution are considered to estimate the environmental cost of this adaptation strategy.

5.3.1.5 Ecosystem-based approaches (AD07)

Ecosystem-based approaches (EbA) make use of ecosystems and biodiversity to adapt to climate change (UNEP, 2019). Agroforestry is one of the EbAs and it integrates crops and trees, either timber or fruit species, in the cropland. This type of strategy is commonly implemented to deal with challenges connected to climate change and water stress as it is recognized as a water-efficient system on irrigated croplands. In addition, it enhances ecosystem services (e.g., cropland water retention, and/or carbon sequestration) and biodiversity (Ghanbari et al., 2021; UNEP, 2019) (Roe et al., 2021). In this chapter, only water retention is captured without considering other ecosystem services. For instance, agroforestry increases infiltration and water retention, and it has been proven by Calvo (2022) that agroforestry requires up to 80% less water for irrigation than a conventional cropland without trees. In the present chapter, agroforestry is only implemented on dairy farms that relies on irrigated croplands, such as the dairy farm in the Mediterranean. It is assumed that timber trees are used in this case study, such as ash and walnut, to be aligned to the activities of the project (LIFE, 2021).

5.3.1.6 Ferrying water (AD09)

The projected water stress in the dairy farm of the Mediterranean region will lead to interbasin water transfer to guarantee the water usage at dairy farm (i.e., cow intake and irrigation), which is 767 m³ every year (Egas et al., 2020). However, it can result in extra electricity usage, and it can cause water shortages or water stress in the basin where the water was extracted from. In order to estimate the extra electricity, it is assumed that the water is transferred from the nearest basin without or with low water stress, which is the Basin Rhône-Méditerranée-Corse located in the South of France 350 km away from the dairy farm under study in the Mediterranean (WRI, 2022). According to Cymbalsky (2015), this type of water supply system in average required 0.08 kWh/m³/km. Based on this information, it is possible to estimate the extra electricity usage.

5.3.1.7 Dig trenches (AD13)

Risk of floodings is expected in the Northern region of Europe (Guzmán-Luna et al., 2023a). Digging trenches can be an effective way to manage and redirect floodwaters and it has identified as an adaptation strategy. Commonly, excavators are required to dig the trenches and this type of machinery run into diesel, which is a resource considered to estimate the environmental cost of this strategy. In addition, the land used to build the trench is also a resource considered as it may have been land that could have been used for other purposes such as cropland. The land use is estimated based on the total area of the dairy farm and by assuming a width of 1 meter. Details on the diesel and land required can be seen in supplementary material of the resulting paper of this chapter. In the present chapter, dig trenches are assumed to be redone every year due to landside or erosion.

5.3.1.8 Fenced perimeter (AD14)

Similarly, due to risk of floodings, fencing the perimeter with the construction low concrete walls is another adaptation strategy identified (De Vries, 2018). However, the environmental cost of constructing this type of structure results insignificant as it has long lifespan, and it is not considered in this chapter. On the contrary, the land required to build it is considered and it is estimated based on the perimeter of the dairy farm and by assuming a width of 1 meter.

5.3.2 Non-quantifiable adaptation strategies

5.3.2.1 Resilient breeds (AD02)

Another adaptation strategy identified to deal with the increasing heat stress events across the two dairy farms under study is the adoption of dairy cow breeds resistant to heat stress. It can be achieved throughout crossbreeding as naturally there are some breeds of dairy cows more heat stress-resistant than others. For instance, the Thai Holstein breed has a temperature humidity threshold of up to 80, which is higher when it is compared to the traditional Holstein breed used in Europe with a threshold of 68 (Boonkum et al., 2011; Fodor et al., 2018). Genomic selection for heat resistant breeds has been also taken place. It allows to select for specific traits associated with heat tolerance (Fodor et al., 2018; Optibarn, 2017). In general, dairy cows more resistant to heat stress can result in less time use of the on-farm cooling systems in indoor systems and when shading is not enough in outdoor systems. However, it resulted impossible to estimate the resource usage of this alternative and their environmental cost due to the lack of data to do so.

Like heat-resistant breeds, research is happening on breeding for resistance to reduce incidence of bovine mastitis. Naturally, there are cow breeds that present strong resistance to mastitis such as the VikingRed (Shonka-Martin et al., 2019). This type of adaptation strategy is then promising for the dairy farm in the Mediterranean and in the Northern region of Europe

as it is expected an increase of pathogen mastitis prevalence across them (Guzmán-Luna et al., 2022).

5.3.2.2 Resilient crops (AD08)

Climate variability, floods, water stress and crop pest infestation are climate hazards that have increased the interest for developing resilient crops and they can be used in agriculture, including dairy farming. Barley, sorghum, and maize are clear examples of crops that have been improved to withstand given climate hazards (Dhankher & Foyer, 2018). However, the quantification of their environmental cost was not possible since no inventory data on resilient crops was identified.

5.3.2.3 Alternative feeds (AD12)

Ongoing research is exploring novel alternatives to traditional feeds for cows, with a focus on the potential use of microalgae (Halmemies-Beauchet-Filleau et al., 2018) and insects, which include the black soldier fly larvae, crickets, and mealworms (Ahmed et al., 2021). This type of feed has promising results as they have demonstrated to possess a high nutritive value, hold environmental advantages, and reduce methane emissions arising from cow enteric fermentation (Ahmed et al., 2021; Phesatcha et al., 2022). So, this is a promising area to keep improving the environmental impact of the dairy industry that has still to be further explored (Ahmed et al., 2021).

5.3.3 Net environmental cost of site-specific adaptation strategies

The resulting net environmental costs (i.e., GW, WU, and LU) of the selected adaptation strategies from Figure 5.5 are described here. Based on it, win-win adaptation strategies are identified and shown in positive numbers in Figure 5.6 and 5.7. Details about the calculations and the material and resource usage considered for each strategy can be found in supplementary material in the resultant paper of this chapter.

Starting with the case study in the Mediterranean, the quantifiable site-specific adaptation strategies include cooling systems (AD01), shifting of locations of on-farm crop production (AD04), new treatment interventions (AD06), EbAs (AD07), inter-basin water ferrying (AD09), and construction of dams or valley tanks to store water (AD10) (Figure 5.6).

The implementation of cooling systems (AD01) resulted in a win-win site-specific adaptation strategy since its environmental cost is offset by saving the raw milk that without the strategy, raw milk would have been lost due to cow heat stress. This strategy has an environmental cost due to the water and electricity required for its implementation. Even with these costs factored in, the net environmental impact of the strategy is still lower than if it was not applied. This is because the environmental impact of saving lost milk through the implementation of the strategy is greater than the environmental impact of the strategy itself. Besides, the energy transition by 2050 plays in favour. Nevertheless, the implementation of this strategy might be challenged by other climate hazards such as water stress, which is projected in this case study by 2050. Therefore, the implementation of strategy AD09 (i.e., water ferrying) and strategy AD10 (i.e., construction of dams or tanks) will be necessary. Here, an increment or decrement was not shown in their net environmental impact, so no environmental cost is identified. Since it does not affect the environmental performance of dairy farms, they can be an alternative to guarantee water for the cooling systems (i.e., AD01) and avoid raw milk losses from heat stress.

In addition, the environmental cost of shifting locations of on-farm crop production (AD4) resulted in an offset only in terms of LU and WU but not for GW. The reason is that crop production in Sweden (i.e., the assumption from this chapter) is not commonly irrigated compared to the crop production at the dairy farm under study in Spain, which is irrigated. Also, higher crop yields are presented in the Northern regions of Europe, meaning lower land used (Hoekstra & Mekonnen, 2010). If GW is to be completely offset, the implementation of transportation modes with lower environmental impact (e.g., electric lorries) is promising.

In addition, the increase in the prevalence of bovine mastitis in the Mediterranean region of Europe will lead to adopting bacteriophages (AD06). However, its net environmental cost resulted in negative values in terms of GW and WU. This is because water is required to dilute and prepare the bacteriophages and transportation is required as it was assumed that bacteriophage was imported. So, this cannot be considered as a win-win strategy.

Then, the adoption of EbAs (AD7) also resulted in another strategy that is completely balanced for the three impact categories. Even though the extra water required for the timber trees, the ecosystem services (i.e., water retention) provided by this strategy made the environmental cost of this strategy offset. Besides, this adaptation strategy has action on the climate hazards: water stress, crop pest and climate variability.

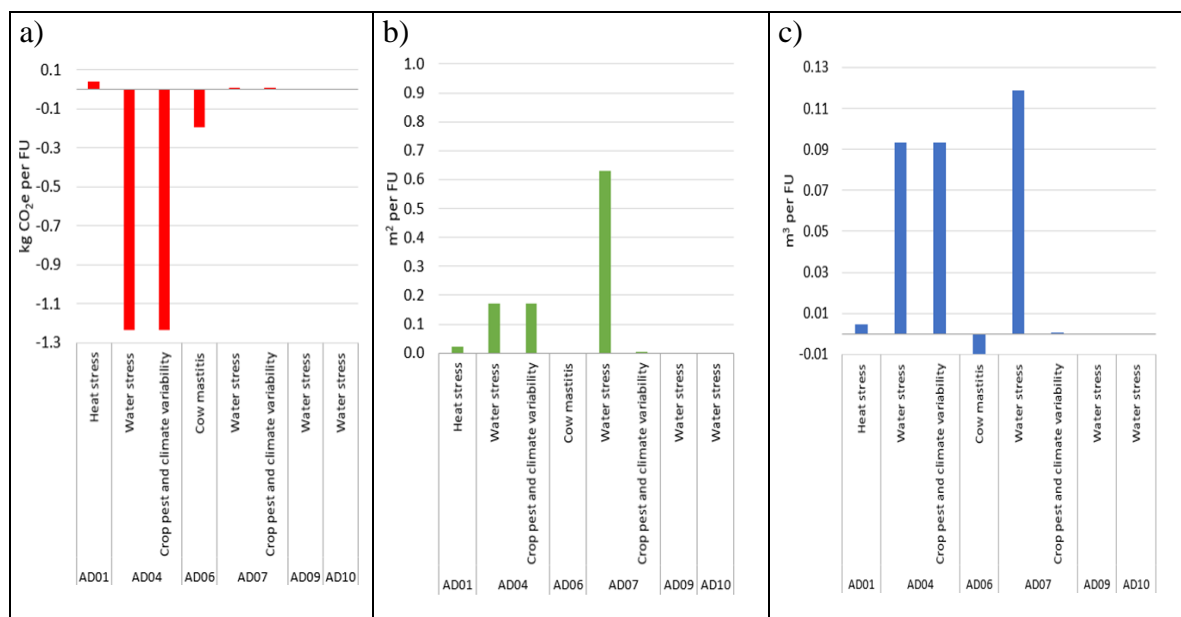


Figure 5.6. Net environmental cost of quantifiable adaptation strategies specific for the dairy farm in the Mediterranean region of Europe. Global warming (a), land use (b), and water use (c).

Moving with the case study in the Northern region of Europe, quantifiable site-specific adaptation strategies include the provision of shade (AD03), new treatment interventions (AD06), construction of dig trenches (AD13) and fencing of the dairy farm perimeter (AD14) (Figure 5.7). Here, crop yield reductions are null and raw milk losses due to heat stress and bovine mastitis are minimal. Regarding heat stress, the provision of shade (AD03) across grazing areas is identified. This strategy means a minimum environmental cost due to the low materials required for the shading structure. In terms of GW, WU and LU, this strategy is completely offset by the benefit it offers (i.e., avoidance of heat stress and raw milk losses). However, this strategy seems to be efficient at a certain point and it may not always be enough. In such conditions, the air temperature and humidity levels may be so high that shade alone

cannot cool cows sufficiently. According to the literature, when there are 8 consecutive days of heat stress, this strategy is no longer effective, and the implementation of heat abatement systems is essential to cope with cow heat stress (Fodor et al., 2018).

Moreover, an increase in the prevalence of bovine mastitis is also projected for the Northern region of Europe. So, bacteriophages (AD06) are also a strategy here; nevertheless, it also presented a negative net environmental cost for three impact categories. Similar to the Mediterranean, the reason is the water used and the transportation required.

Finally, floods are expected to occur and affect the dairy farm under study. Here two adaptation strategies are identified. The first is the implementation of dig trenches (AD013) in which diesel from the excavator and land are the two resources considered. The second adaptation strategy is the construction of a concrete short wall (AD014) around the dairy farm perimeter. Here the use of land is considered as a resource. Even though diesel and land are required, the net environmental cost of these two adaptation strategies was offset in terms of the three impact categories (Figure 5.7) due to the minor portion that the small wall requires.

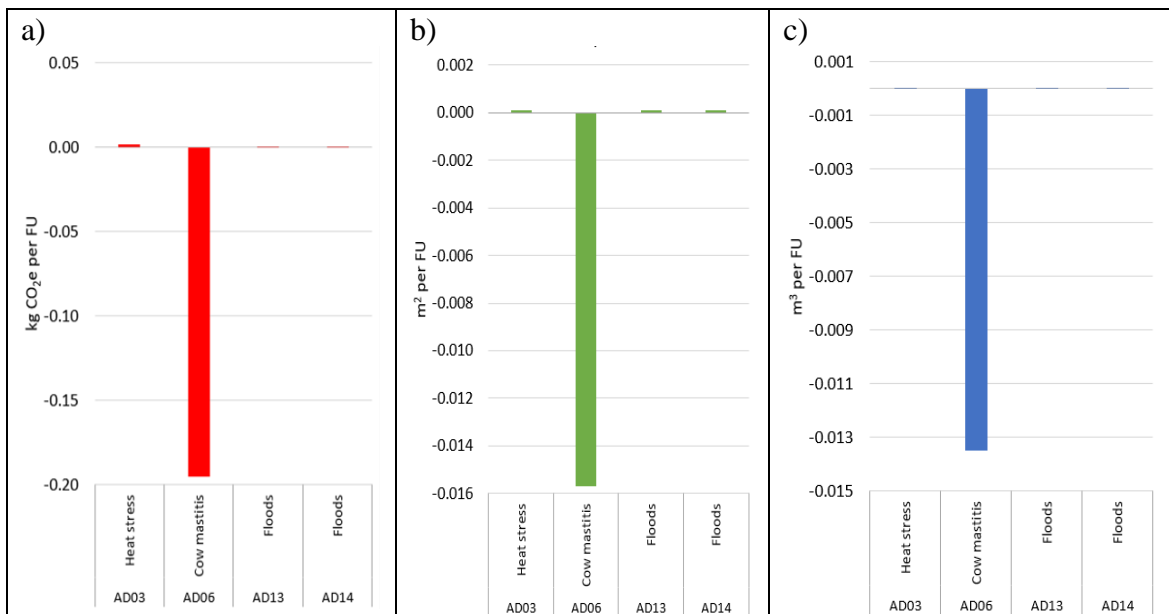


Figure 5.7. Net environmental cost of quantifiable adaptation strategies specific for the dairy farm in the Northern region of Europe. Global warming (a), land use (b), and water use (c).

5.4 RECOMMENDATIONS: INTEGRATION OF METHODOLOGIES FOR WIN-WIN ADAPTATION STRATEGIES

In an era of climate change, the adoption of efficient adaptation strategies is challenging as they do not only need to look at adapting to the site-specific climate hazards but also at doing it at a lower environmental impact and ensuring food safety. To achieve win-win site-specific adaptation strategies, the estimation of their net environmental costs is required. To do so, the integration of methodologies and tools is promising in dealing with this complex challenge.

The integration of energy models into LCA is promising to quantify the net environmental cost of adaptation strategies. Energy models can serve to evaluate adaptation strategies that



require energy to operate. For instance, heat abatement systems are required to relieve the increasing heat stress events across dairy farms in Europe. Energy models can be implemented for assisting with energy optimization (Malliaroudaki et al., 2022; PROTECT-ITN, 2022), and thus, they can serve to optimize heat abatement systems, leading to a potential improvement of their environmental impact. So, by including energy models, raw milk losses due to cow heat stress can be diminished or even avoided at lower energy consumption. An additional benefit of integrating energy models at the dairy farm stage is the generation of site-specific data required for LCA, as in some cases, the data remains unavailable.

In addition, the incorporation of ecosystem services models into the evaluation of the net environmental cost of adaptation strategies is also promising. In this chapter, only water retention is captured for the implementation of agroforestry. But carbon sequestration is also part of the benefits provided by this type of strategy. The integration of it might influence the net environmental impact of another adaptation strategy or even offset the environmental cost of a given strategy. In general, the integration of ecosystem services can benefit the actual load of the dairy farm's environmental impact and/or avoid underestimations (Rugani et al., 2019).

Finally, adaptation strategies also mean an economic cost for the dairy farmer and the implementation of some of the strategies might cause a dilemma in the farmer's acceptance. So, a multi-criteria decision analysis is another promising approach to bring economic cost and dairy farmer acceptance into the equation of win-win adaptation strategies (Feliciano et al., 2023).

5.5 CONCLUSIONS

Dairy farms across Europe are expected to be unevenly affected by the unavoidable impacts of climate change, and thus, the need for site-specific adaptive capacity is clear.

In an era of climate change where clear goals have been defined, adaptation strategies need to take a step forward and strategies that look beyond just adjusting to the site-specific impacts of climate change need to be fostered. They must also ensure food safety with a low environmental impact. The design of win-win adaptation strategies that look at these aspects can contribute to the global Sustainable Development Goals, and they can directly be linked to Goal 2 (i.e., zero hunger and sustainable agriculture), Goal 6 (i.e., ensure availability and sustainable management of water), Goal 12 (i.e., responsible consumption and production), Goal 13 (i.e., climate action), and Goal 15 (i.e., protect, restore and promote sustainable use of ecosystems).

The integration of methods and tools is promising to identify the net environmental cost of adaptation strategies, and thus, identify win-win adaptation strategies for site-specific climate hazards. But before starting adaptive capacity, a depth understanding of the climate hazards and their biophysical impacts at the dairy farm under study is necessary. This chapter beyond evaluating adaptation strategies also seeks raising the urgency to the dairy sector of paying attention to the implementation of adaptation strategies since they have not been very explored in comparison to mitigation strategies.

6. TOOLBOX APPLICATION AT A COMPANY CONTEXT

SUMMARY

In this chapter, the toolbox developed in Chapter 4 is applied at a company context to disclose information related to impacts of climate change at the largest worldwide dairy cooperative: Arla Foods.

All relevant information was communicated following the framework of the Task Force on Climate-Related Financial Disclosures (TCFD), which recommends disclosing the information related to four pillars: governance, strategy, risk management, and metrics and targets. However, the TCFD does not indicate the tools, methods, or models to do so. Therefore, module 2 (i.e., Assessment of climate hazards and their biophysical impacts at the dairy farm) from toolbox of Chapter 4 was used. The impacts of climate change were disclosed for Arla Foods dairy farming main countries (i.e., United Kingdom, Germany, Sweden, and Denmark).

Besides, the mathematical models developed in module 2 for milk losses due to cow heat stress and mastitis were transferred into a user-friendly tool, so the Corporate Finance Department, who oversees reporting the TCFD, can use it in their future disclosures.

This chapter was the result of the industrial secondment at Arla Foods under the supervision of Dr. Anna Flysjö from the Department Global Sustainability and Anna Csonka and Janni Opstrup from the Corporate Finance Department. Also, as part of the evaluation of this type of work, this disclosure was reviewed by EY, an international audit firm.

- Guzmán-Luna, P., Flysjö, A., Csonka, A., and Opstrup, J. (2022). Climate related-risks and opportunities from physical hazards across Arla dairy farms. Reported as Task Force on Climate-Related Financial Disclosure in the Arla Annual Report 2022 (Confidential report).

6.1 INTRODUCTION

Climate change is one of the most urgent issues that the world is facing today. As part of the European Green Deal, the Corporate Sustainability Reporting Directive (CSRD) is one of the key initiatives that seek to improve transparency and consistency of reporting among companies (EC, 2022). It is expected that companies must disclose information on their environmental, social, and governance practices, including their contributions to climate change and their impacts related to climate change. In this sense, there is a clear interaction between climate change and the dairy sector, which contributes to climate change but it is also affected by this global issue (Guzmán-Luna et al., 2021). In this context, the CSRD will play a significant role in pushing the dairy sector to report their contributions to global warming and the impacts of climate change on this sector. To date, dairy companies have been investigating and tracing their contribution to global warming and significant improvements have been achieved through the implementation of mitigation strategies (EDA, 2018a). Nevertheless, dairy industries have not adequately investigated the effects of climate change on their operations (Guzmán-Luna et al., 2023b), and this lack of information might be a serious challenge for complying with the CSRD, which is expected to become mandatory, as well as adapting to the unavoidable effects of climate change.

Given the growing urgency of climate change and its potential impacts on companies, the Task Force on Climate-related Financial Disclosures (TCFD) has been launched in 2017 by Financial Stability Board and it looks at providing a framework for companies around the world to disclose their climate risks and opportunities (FSB, 2022). It has been used for improving the climate-related disclosures of companies and performing their CSRD. Within the TCFD, hazards that a company can face are classified into transitional and physical hazards¹, and they will induce risks and opportunities. Transitional hazards refer to all climate actions likely to occur in the transition to a low-carbon economy, such as technology shifts, legislative adaptation, regulation application, and consumer behaviours. Physical hazards result from the physical effects of climate change such as an increase of temperature, modification of rainfall patterns, and rise of sea level.

Arla Foods (www.arla.com) is one of the largest producers of dairy products and an international dairy cooperative, i.e., it is owned by dairy farmers located across different countries in Europe. This cooperative has stated its commitment to environmentally sustainable dairy farming practices and reducing its environmental impact by implementing science-based targets (Arla Foods, 2022a). For instance, reaching carbon net zero by 2050 is one of the global ambitions set by this dairy cooperative (Arla Foods, 2022b).

Physical hazards can impact the dairy products value chains of Arla Foods, mainly at the dairy farm stage, challenging its performance and modifying raw milk production. As presented in chapter 1, physical hazards include water stress, permanent and flash floodings, increasing of temperatures, modification of precipitation patterns and pathogen and pest growth (Guzmán-Luna et al., 2021). However, as described in chapter 4, physical hazards will unevenly impact European regions (i.e., Northern, Continental, Atlantic and Mediterranean), and thus, climate-related risks and opportunities across Arla dairy farms will also vary.

Previous chapters have shown that there is clear evidence that climate change will affect the dairy sector. The effects of this global issue will be unavoidable and initiatives, such as

¹ “Physical hazards” is the same term to refer to climate hazards as done in the rest of the thesis. But in this chapter, the term “physical hazards” is used to align it to the terminology of the TCFD. Only physical hazards are covered, leaving transitional hazards out of scope, as they were covered by the Corporate Finance Department of Arla Foods.

CSRD, will push this sector to disclose them. Thus, this chapter aims to support the dairy industry in identifying, evaluating, and understanding the impacts of climate change posed by physical hazards. This information will allow to define the different directions that Arla Foods may encounter in a climate change era full of uncertainty by 2050.

As the impacts of climate change on this dairy cooperative had not been addressed previously, this work is the first stone to build Arla’s adaptative capacity to climate change. Specifically, this chapter looks at giving answer to the following questions:

- What will be the possible scenarios that Arla might encounter by 2050?
- How does Arla identify and estimate the physical hazards and their biophysical impacts on its dairy farms under the different scenarios?
- What are the risk and opportunities identified for Arla dairy farmers across the different regions?
- What is the likelihood that the identified risk and opportunities will occur?

6.2 TCFD FRAMEWORK

To disclose the impacts of climate change at Arla Foods and align with the CSRD, the framework from the TCFD (Figure 6.1) is followed (FSB, 2022). It recommends disclosing given impacts on four areas.

The first area is Governance. It refers to the corporate’s governance, and to how it oversees climate-related risks and opportunities at the board and management levels. Then, the metrics and targets area assess the impacts of climate change in a defined temporal horizon and describes the methods and information sources that a company implements to do so as well as to trace its progress toward achieving potentially previously defined targets. The next area is Risk Management, which involves the description of the climate-related risks and opportunities of the company. Lastly, the Strategy area looks at defining a plan for managing the risks and leveraging the opportunities that the company might face.

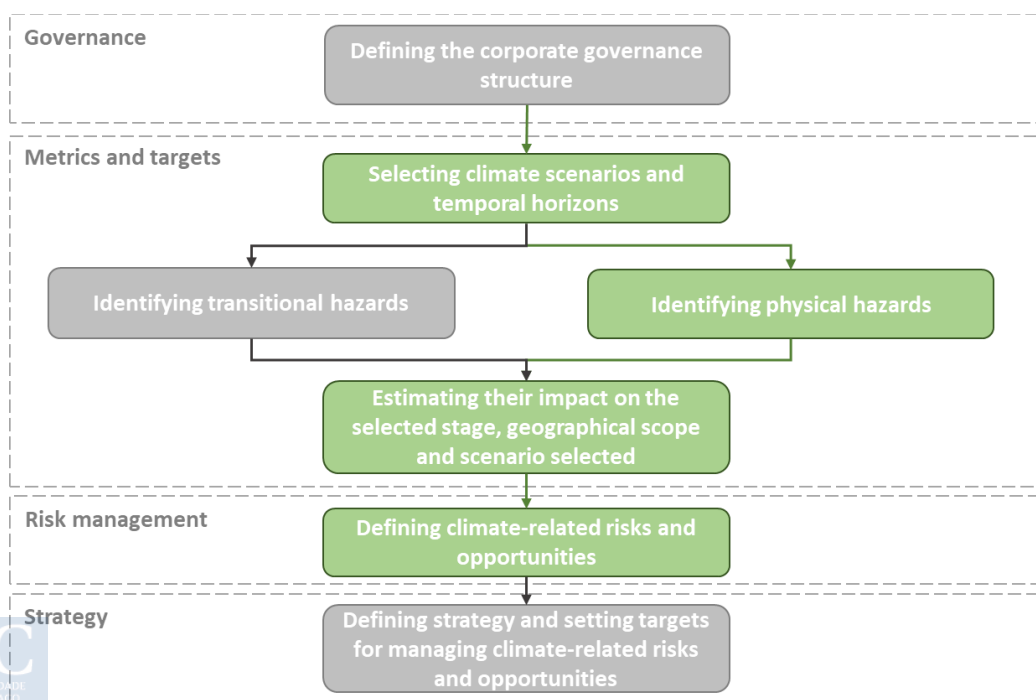


Figure 6.1. TCFD framework to assess impacts of climate change. Green boxes show the contributions of module 2 (chapter 4). Grey boxes refer to the activities for which the CFD was responsible for.

At an Arla Foods context, the first area, which corresponds to the corporate structure definition, was previously carried out by the Corporate Finance Department (CFD) of Arla Foods. As part of the corporate structure, Arla dairy farmers are spread across seven European countries (i.e., United Kingdom (UK), Germany, Sweden, Denmark, Luxembourg, the Netherlands, and Belgium), being the most productive regions, the ones shown in Figure 6.2: Centre of Sweden, Denmark, southwest of Germany, and west of UK.



Figure 6.2. Biogeographical regions in Europe defined by EEA (2017) and most productive regions (red boxes) according to their total annual raw milk production in 2021.

In the second one, the metrics used to assess the impacts of climate change at the cooperative are described and this part of the framework interacts with module 2 of chapter 4 (as further described in section 6.3 of this chapter). At this point, targets have not yet been defined as the dairy cooperative is in its first phase of implementing the climate-related risks and opportunities assessment. Then, the third area looked at defining the climate-related risks and opportunities based on the assessment previously done (as described in section 6.4).

The last area, which defines the strategy to deal and manage given risks and opportunities, is not covered in this research step. It is an activity in which the corporation (e.g., the CFD, the Executive Management Team, and the Board of Directors) is responsible for and it is under progress.

6.3 METRICS AND TARGETS

As climate hazards and their impacts will vary among climate scenarios and temporal horizons, this is the starting point of the quantification:

Plausible scenario: SSP2-4.5 scenario by 2050 (IPCC, 2022) is selected based on the company interest and its relevance and feasibility in terms of data availability. It implies that

by mid of this century, the global average temperature might increase by 1.4 °C (Figure 1.3 from chapter 1).

Extreme scenario: SSP5-8.5 scenario by 2050 (IPCC, 2022) is also included as the TCFD recommends so. Here, the global average temperature is expected to increase by 2 °C (Figure 1.3 from chapter 1).

Once the climate scenario and temporal horizon were set, relevant physical hazards at the dairy farm level were identified based on Guzmán-Luna et al. (2021) (Chapter 1). A description of each of the physical hazards is provided in the following subsections as well as the estimation of their magnitude.

The TCFD only recommends tools or methods to cover a few climate hazards, such as water stress, leaving the others for companies to develop and apply their own methodologies appropriate for their specific context, business model, and sector (FSB, 2022). To cover these gaps, the set of tools presented in Chapter 4 (Guzmán-Luna et al. (2023) was used and integrated with the TCFD recommendations, as summarized in Table 6.1:

Table 6.1. Methods and data sources used to estimate physical hazards and their biophysical impacts according to the toolbox developed by Guzmán-Luna et al. (2023).

Physical hazard	Method or data source	Resulting biophysical impact	Method or data source
Water stress	Aqueduct (World Resources Institute, 2022)	Changes water provision profile	WSmix (Leão et al., 2019)
Floods (permanent and flash)	Aqueduct (World Resources Institute, 2022) and maps from European Environment Agency (2022)	Changes in crop geographical distribution	Rosegrant et al. (2017)
Crop pest infestation	Data from literature: Tepas-yotto et al. (2021), Zacarias (2020) and Gilioli et al. (2022)	Changes in crop yield	Data from literature: Tepas-yotto et al. (2021), Zacarias (2020) and Gilioli et al. (2022)
Climate variability	Hristov et al. (2020)	Changes in crop yield	Hristov et al. (2020)
Cow heat stress	This work (Chapter 4, Guzmán-Luna et al., 2023)	Changes in raw milk losses	This work (Chapter 4, Guzmán-Luna et al., 2023)
Cow diseases	This work (Chapter 4, Guzmán-Luna et al., 2023)	Changes in raw milk losses	This work (Chapter 4, Guzmán-Luna et al., 2023)

6.3.1 Water stress

The TCFD recommends the use of Aqueduct 3.0 as a tool to provide information on water stress across companies, and the same tool was previously used in the toolbox in chapter 4. Water stress has a direct impact on the dairy farm but also an indirect on crop production. Water stress is a site-specific physical hazard that is expressed in percentage and only valid for the region of study (Table 6.2). Values greater than 100% mean that no groundwater and surface water is available to satisfy the needs of the different sectors in a specific region. Thus, a region under water stress has lack of freshwater available to comply with the needs of herds and irrigated crops, and farmers in that area must resort to the use of other water sources such as external or non-conventional sources. However, these solutions can result in an extra electricity cost (for example when extensive pumping is employed depending on the water supply technology), as well as result in water stress in the region where water is being extracted from.

Also, water stress, together with other physical hazards (i.e., floods, crop pest infestation, and climate variability), can lead to changes in the geographical distribution of crops, changing

the location of productive regions in the world and affecting Arla dairy farmers as they rely also on off-farm feedstuff. However, an accurate projection on the future location of productive crop areas is quite complex as many other climate and non-climate related factors are involved and remain uncertain. To address this, the IMPACT model developed by Rosegrant et al. (2017) has been used to analyse potential productive areas of several crops by 2050, considering physical hazards as well as land-use change. After an extensive literature review, this model was selected since it includes climate change variables, food security and potential policies in its projections. In general, crop areas will be expanded in developing countries as the forest area is expected to be reduced. For instance, there will be crop area expansion for cereals in South of Africa and South America due to a decrease of forest area. Similarly, the crop area for oilseeds will increase in South America, Africa, Middle East, and East Asia. Also, an increase of the roots and tubers area is expected across South Africa and South Asia.

Table 6.2. Water stress in different climate scenarios by 2050.

Arla Food region	Likely scenario SSP2-4.5	Extreme scenario SSP5-8.5
Centre of Sweden	12.5%	11.2%
Denmark	6.4%	6.2%
Southwest of Germany	16.0%	13.5%
West of UK	16.0%	14.5%

6.3.2 Floods (permanent and flash)

Floods are mainly linked to a negative impact on agricultural land. However, the quantitative analysis of floods remains out of the scope of this chapter although it is acknowledged that they will have a significant impact on the agriculture sector at the end of the century (IPCC, 2022). Despite that, it is addressed from a qualitative point of view and discussion on the potential impacts of flash and permanent floods that can affect Arla dairy farms is provided in this subsection.

Flash floods due to extreme events, such as heavy precipitation, are expected to increase in some regions of Europe. Severe winter heavy storms will increase in the continental and northern regions (EEA, 2016), resulting in flash floods that can negatively impact the crops grown across Arla dairy farms located in Sweden, Denmark, and Germany. Floods during winter can wash away the land and destroy on-farm crops and lead to a change in the availability of the on-farm feed and dairy farmers might need to rely on another feedstuff. Coastal floods due to sea level rise are expected to impact coastal areas of the Atlantic region, mainly the Netherlands, east of UK, north of Germany, and Denmark, by the end of the century. Floods will result in the inundation of deltas areas and the loss of wetlands and marshes across these regions, affecting productive lands. Besides, another negative impact of coastal floods is the salinity intrusion that will affect crop yield and quality. It occurs when the sea level rise along the coasts and the saltwater enters the land through the coastal aquifers (EEA, 2017). Thus, Arla dairy farmers that grow their on-farm feed along these areas will also experience lower crop yields and quality due to unsuitable soil conditions.

6.3.3 Crop pest infestation

The geographical coverage of crop pests is expected to spread due to changes in climate conditions, leading to crop yield reductions and even crop physical losses. Information from literature was used to observe the projections of crop pests in the future, and the papers are described in Table 6.1. According to the literature, the *Spodoptera frugiperda* is one of the most relevant pests since it causes damage to more than 350 plant species (EC, 2019). This mobile pest has spread to all the continents all over the world, but it has not settle in Europe yet (FAO,

2021). However, it is expected to become alarming for the European agriculture sector in the future as its settlement is forecast by 2050 in Europe, including the Atlantic and Continental regions (Tepa-yotto et al., 2021; Zacarias, 2020). Thus, Arla dairy farmers in the Southwest of Germany and West of UK must add this climate hazard to their agenda, while farmers in Denmark and Sweden will be spared (Table 6.3).

Table 6.3. Crop yield reduction due to *S. frugiperda* invasion in different scenarios by 2050.

Arla Food region	Likely scenario SSP2-4.5	Extreme scenario SSP5-8.5
Centre of Sweden	No losses	No losses
Denmark	No losses	No losses
Southwest of Germany	9.0%	11.0%
West of UK	9.0%	11.0%

6.3.4 Climate variability

Extreme weather events and climate variability are expected to alter crop yield and data from literature was used to estimate changes in crop yields (Table 6.4). Decrements in crop yields are represented with a negative sign, whereas positive ones are represented with a positive one. This physical hazard was categorized as a long-term period as the modification of the crop yield is projected to occur by 2050 or later (Ray et al., 2019).

Most of the regions will be negatively affected by these climatic condition changes and very few others, such as the Northern region, will benefit.

Table 6.4. Crop yield reduction due to climate variability and extreme weather events in different scenarios by 2050.

Arla Food region	Likely scenario SSP2-4.5	Extreme scenario SSP5-8.5
Centre of Sweden	+5.0%	+5.0%
Denmark	+15.0%	+5.0%
Southwest of Germany	-17.5%	-17.5%
West of UK	+5.0%	-5.0%

6.3.5 Cow heat stress

An increase in temperature and relative humidity due to climate change will increase the frequency with which cows experience heat stress, leading to decreased raw milk yield. An available model was adjusted to the geographical location and climate scenarios of interest. The obtained results are shown in Table 6.5. The model requires input data, including maximum temperature and relative humidity as mentioned in Chapter 4, and annual milk yield, which is obtained directly from the dairy cooperative. Cow heat stress is considered as a long-term physical hazard that is expected to cause significant raw milk losses by 2050 approximately.

In some areas of Europe raw milk losses due to cow heat stress is already a reality, and dairy farms located across the Mediterranean region are dealing with it. However, Arla dairy farmers located will also experience raw milk losses at their farms by 2050, being German farms the most affected.

Table 6.5. Annual raw milk losses due cow heat stress in different scenarios by 2050.

Arla Food region	Likely scenario SSP2-4.5	Extreme scenario SSP5-8.5
Centre of Sweden	0.18%	0.31%
Denmark	0.06%	0.17%
Southwest of Germany	1.17%	1.87%
West of UK	0.11%	0.27%

The estimation of Table 6.5 results is based on a mathematical model, which has been implemented in Matlab, a barrier to its use without a certain expertise. To enhance its applicability at company level, the model was transferred into a user-friendly application with a graphical user interface (Figure 6.3). This application also estimates raw milk losses due to mastitis using the mathematical model described in the following section. This user-friendly application was delivered to the Corporate Finance Department of Arla Foods, as they are responsible for disclosing climate-related risks and opportunities.

The mathematical model to estimate raw milk losses from heat stress is described in detail in chapter 4. This model first estimates the monthly temperature-humidity index (THI). The inputs required are maximum temperature and relative humidity. When this information is not available at the dairy cooperative, this research refers to the World Bank Group (2021), which is a database to obtain projected climate data for different climate scenarios and temporal horizons around the world. Then, climate data can be introduced in the first column of the application (Figure 6.3). Next, raw milk losses are estimated in which the temperature-humidity threshold of the cow is defined. According to the expert opinion from the dairy cooperative, it was set at 68 but it can be modified in the list of required data of the application (Figure 6.3). Once the inputs required for the two equations are filled in, three outputs can be obtained. If the THI estimated does not exceed the cow threshold (e.g., 68), a green light turns on; however, when it exceeds the threshold, the light will turn red. It allows for identifying easier which months of the year will be more susceptible to raw milk losses. Then, raw milk losses are also shown in the form of a kilogram of FPCM and annual percentage of losses.

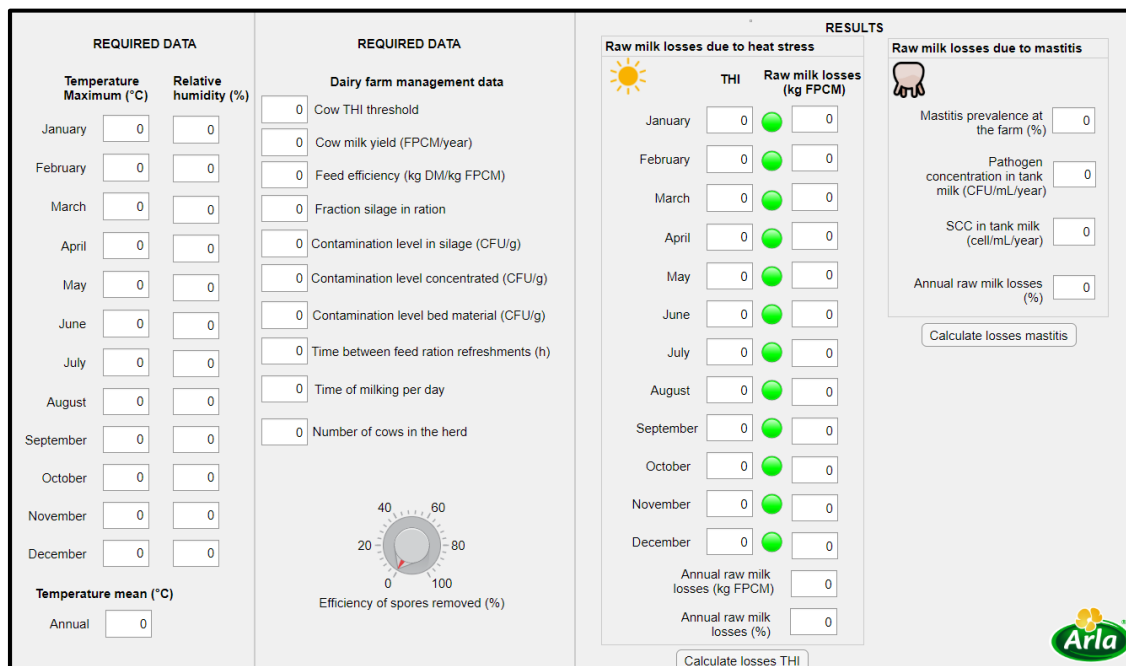


Figure 6.3. Visual representation of the developed user-friendly application.

6.3.6 Cow diseases

An increase of temperatures, a change in precipitation patterns and a modification of relative humidity are expected to promote the contamination and growth of pathogens that can lead to bovine mastitis and result in decreased raw milk yield. Similarly, due to the lack of models, a mathematical model was developed to predict raw milk losses due to mastitis caused by *Staphylococcus aureus* under different climate scenarios, regions, and time horizons.

Detailed information on the predictive model can be found in Chapter 3. Raw milk losses due to bovine mastitis are considered a long-term period in this research.

Prevalence of *Staphylococcus spp.* and other pathogenic microorganisms already occurs across European dairy farms; however, the prevalence is expected to increase by 2050. According to the obtained results from the model (Table 6.6), dairy farms located in the west of UK will be the most affected by this pathogen, and thus, the ones that will experience the highest percentage of raw milk losses.

Table 6.6. Annual raw milk losses due bovine mastitis in different scenarios by 2050.

Arla Food region	Likely scenario SSP2-4.5	Extreme scenario SSP5-8.5
Centre of Sweden	1.44%	1.51%
Denmark	1.49%	1.52%
Southwest of Germany	1.83%	1.89%
West of UK	1.99%	2.03%

The model to estimate raw milk losses from bovine mastitis refers to the investigation carried out in chapter 3 and the inputs are shown in Table 3.1. However, data of some of these inputs (e.g., pH of the feed ration, the mean concentration of mastitis pathogen in the feedstuff and bedding material) were not available at Arla Foods, so they were set by default based on data from the literature. Values are shown in Table 3.1. On the contrary, the inputs from Table 3.1 about which Arla Foods had information were set as parameters in the application. Once the inputs are added into the second “Required data” column of the application (Figure 6.3), four outputs can be obtained: the percentage of mastitis prevalence at the analysed dairy farm, pathogen concentration in the tank milk, the somatic cell count in the tank, and annual raw milk losses (Figure 3.1 from chapter 3). The code can be seen in the authors github ².

6.4 RISK MANAGEMENT

Climate-related risks and opportunities are described in Table 6.7. Whereas risks are highlighted in orange, the opportunities are remarked in green. Also, the level of certainty is added for each of the defined risks and opportunities following the recommendations of the IPCC (2022). The 6th report of the IPCC mentions that the degree of confidence can be evaluated and communicated based on the evidence and scientific agreement of the obtained information or data. Agreement is scored in low, medium, and high and it evaluates to what extent the different sources of information agree and do not contradict each other. Evidence is scored in low, medium, and robust, and it considers the type and quantity of evidence gathered. Following an agreement and evidence matrix, then, confidence can be evaluated according to the five scores proposed by the IPCC: very low confidence, low confidence, medium confidence, high confidence, and very high confidence. Then, meetings were organized with the Corporate Finance Department to set a score to each of the identified climate-risk and opportunities in the table below. The score was assigned based on proper knowledge and discussions. Later, these scores were validated with the international auditory EY as described in detail in section 6.5 of this chapter.

Table 6.7. Risks and opportunities identified for the different selected regions as well as their degree of certainty.

Country	Risk	Certainty level	Opportunity	Certainty level
Centre of Sweden	Higher raw milk losses due to cow heat stress in summer	Very high confidence	Potential increase of crop yields and their quality and	Medium confidence

² <https://github.com/paolaguzmanluna>

			winter grazing due to warmer winters	
	Raw milk losses due to higher prevalence of mastitis	High confidence	Potential introduction of crops as winter become warmer	High confidence
	Flash floods in winter that destroy on-farm feed and lead farmers to rely on off-farm feedstuffs	Medium confidence	Warmer and shorter winters due to climatic extremes expected lead to a reduction energy for heating the barn	High confidence
Denmark	Higher raw milk losses due to cow heat stress in summer	Very high confidence	Potential introduction of crops as winter become warmer	High confidence
	Raw milk losses due to higher prevalence of mastitis	High confidence	Warmer and shorter winters due to climatic extremes expected lead to a reduction energy for heating the barn	High confidence
	Flash floods in winter that destroy on-farm feed and lead farmers to rely on off-farm feedstuffs	Medium confidence	Potential winter grazing due to increase of temperatures	Medium confidence
	Loss of productive areas and salinity intrusion due to permanent floods (mainly west coast)	Medium confidence		
Southwest of Germany	Higher raw milk losses due to cow heat stress in summer	Very high confidence	Warmer and shorter winters due to climatic extremes expected lead to a reduction energy for heating the barn	High confidence
	Raw milk losses due to higher prevalence of mastitis	High confidence	Potential winter grazing due to increase of temperatures	Medium confidence
	Flash floods in winter that destroy on-farm feed and lead farmers to rely on off-farm feedstuffs	Medium confidence		
	Introduction of <i>S. frugiperda</i> , leading to crop losses	Very high confidence		
West of UK	Higher raw milk losses due to cow heat stress in summer	Very high confidence	Warmer and shorter winters due to climatic extremes expected lead to a reduction energy for heating the barn	High confidence
	Raw milk losses due to higher prevalence of mastitis	High confidence	Potential winter grazing due to increase of temperatures	Medium confidence
	Introduction of <i>S. frugiperda</i> , leading to crop losses	Very high confidence		

6.5 VALIDATION AT THE AUDIT

From 2022, Arla Foods has started to disclose the impacts that climate change poses to the dairy cooperative under the TCFD framework (FSB, 2022). This chapter is then the first attempt in identifying climate hazards and estimating their biophysical impacts by using data sources that allow giving a site-specific assessment. So, in order to provide assurance on the accuracy, completeness, and reliability of the climate-related disclosure performed by the company, an audit with the EY firm was part. The audit was divided into two blocks composed of several sessions each of them.

The main purpose of the first block was to revise the technical aspects of the data sources utilized in Table 6.1. Since the information about water stress, floods, crop pest infestation and climate variability were obtained from already available data sources (i.e., tools and literature), no validation was required and only an explanation of them was given. However, the models

for cow heat stress and diseases were a contribution from this research, and thus, a deeper explanation was provided during the audit. A presentation was carried out to explain the model to estimate raw milk losses due to cow mastitis (chapter 3) and heat stress (chapter 4). At this point, the equations used in those two chapters were explained together with the code of the user-friendly tool to make sure that they both matched. Also, the Matlab code was shared with EY (further details in annex section of this chapter).

Then, the second block of the audit aimed to revise the results reported in this chapter, specifically from Table 6.2 to Table 6.7. The results were double-checked by one auditor of the firm as well as the climate scenarios and temporal horizons to make sure they are consistent with the TCFD framework.

6.6 CONCLUSIONS

This chapter was the opportunity to apply the developed toolbox in a real case, working adequately according to the audit. The results from the toolbox gave clear evidence that climate change and its climate hazards will represent risks and opportunities to Arla dairy farmers differently depending on their country. Sweden, which is located within the Northern region, is identified as a country least affected by climate change in comparison with the other three Arla countries analysed. The identification of opportunities across this country will aid Arla dairy farmers to seize the given opportunities. Unfortunately, climate change will bring more risks than opportunities across Arla dairy farms. To respond to climate-related risks, adaptation strategies are required; however, these can also be associated to a use of resources and a generation of emissions that can modify the environmental sustainability of the dairy sector, leading to a feedback loop between the problem and its solution. In this context, Arla dairy farm will have two challenges: to adapt to climate change keep improving its environmental sustainability. The recommendation is that Arla dairy farmers include in their agenda the implementation of environmentally friendly strategies to adapt to climate change while mitigating the contribution to this global issue.

The estimation of physical hazards and the identification of risks and opportunities seek to support to Arla in developing adaptive capacity to respond to physical risk, as well as seize the potential opportunities. Also, it highlights that adaptive capacity needs to be designed by developing environmentally friendly adaptation strategies that also reduce the environmental impact of dairy farms. Moreover, it is recommended to look at non-physical factors, such as transitional hazards related to regulations, consumer behaviour, and technology, since risks and opportunities can also be triggered by them. These hazards are also to be considered when developing adaptive capacity in Arla as the dairy cooperative will navigate through new regulatory and legislative adaptation that can push dairy farmers to modify their activities, affecting their production and reducing their profitability.

6.7 ANNEX

This section describes the Matlab code behind the user-friendly tool. This code is open and available in the author's github³. Figure 6.4 shows its structure as a guide for the user. Before

running the code for estimating raw milk losses from cow mastitis and heat stress, two essential steps have to be done.

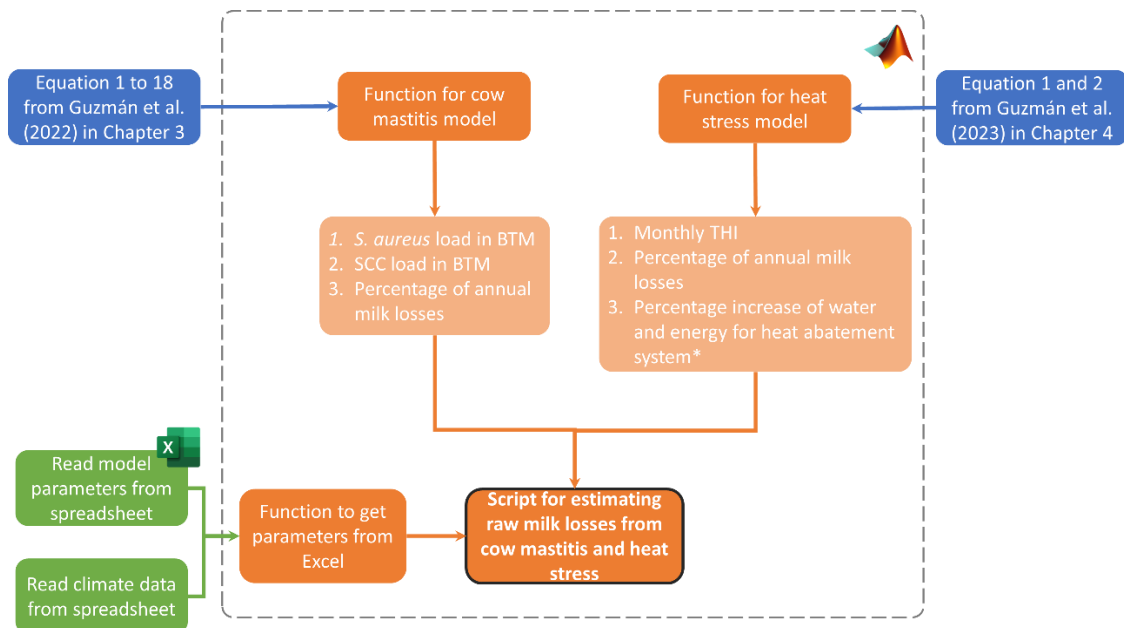


Figure 6.4. Structure of the cow bovine mastitis and heat stress model in Matlab. The two light orange boxes refer to the outputs obtained from the two functions. The third output with an asterisk is not an output added in the user-friendly tool it is part of the model and used in Chapter 5.

In the first step, the user first has to fill in the necessary data in the excel file as shown in the yellow section of Figure 6.5. This data is mainly monthly climate data and dairy farm data such as the number of lactating cows in the herd, their annual milk yield production, temperature-humidity (THI) threshold of the cow, and other data. When it is not available, a data source is recommended in the excel file and also default data is provided. In this case, the default data was the pathogen contamination in feedstuffs, which was obtained from literature (Tables 3.1 and 3.3 from Chapter 3). Then, the user read the data from the spreadsheet, and transfer it to Matlab code as described below.

Abb	Name/meaning	Value	Units	Model	Data source
tempMaxJan	Temperature maximum of month 1	12.58	C	Heat stress	World Bank Group
tempMaxFeb	Temperature maximum of month 2	13.59	C	Heat stress	World Bank Group
tempMaxMar	Temperature maximum of month 3	15.58	C	Heat stress	World Bank Group
tempMaxApr	Temperature maximum of month 4	18.29	C	Heat stress	World Bank Group
tempMaxMay	Temperature maximum of month 5	22.24	C	Heat stress	World Bank Group
tempMaxJun	Temperature maximum of month 6	27.58	C	Heat stress	World Bank Group
tempMaxJul	Temperature maximum of month 7	31.97	C	Heat stress	World Bank Group
tempMaxAug	Temperature maximum of month 8	32.15	C	Heat stress	World Bank Group
tempMaxSep	Temperature maximum of month 9	27.33	C	Heat stress	World Bank Group
tempMaxOct	Temperature maximum of month 10	21.45	C	Heat stress	World Bank Group
tempMaxNov	Temperature maximum of month 11	16.34	C	Heat stress	World Bank Group
tempMaxDec	Temperature maximum of month 12	13.48	C	Heat stress	World Bank Group
relHumJan	Relative humidity of month 1	78.17	%	Heat stress	NASA
relHumFeb	Relative humidity of month 2	74.99	%	Heat stress	NASA
relHumMar	Relative humidity of month 3	72.07	%	Heat stress	NASA
relHumApr	Relative humidity of month 4	70.04	%	Heat stress	NASA
relHumMay	Relative humidity of month 5	68.07	%	Heat stress	NASA
relHumJun	Relative humidity of month 6	64.46	%	Heat stress	NASA
relHumJul	Relative humidity of month 7	63.50	%	Heat stress	NASA
relHumAug	Relative humidity of month 8	65.86	%	Heat stress	NASA
relHumSep	Relative humidity of month 9	71.26	%	Heat stress	NASA
relHumOct	Relative humidity of month 10	75.85	%	Heat stress	NASA
relHumNov	Relative humidity of month 11	76.76	%	Heat stress	NASA
relHumDec	Relative humidity of month 12	79.14	%	Heat stress	NASA
benWatUse	Benchmark global water use	4612.74	L/cow/year	Cow mastitis	Literature
thiThr	THI threshold	68.00	NA	Cow mastitis	Expert's opinion and literature
benEneUse	Benchmark global energy use	40.86	kWh/cow/year	Cow mastitis	Literature
annMilkYield	Theoretical annual milk yield per cow	8154.00	kg of FPCM/cow	Cow mastitis	Literature
benFsilage	Benchmark fraction silage in ration	72.00	%	Cow mastitis	Literature
benContSilage	Benchmark Mean contamination level in silage	3.16	CFU/g	Cow mastitis	Literature
benContFeed	Benchmark Mean contamination in other feeds	3.16	CFU/g	Cow mastitis	Literature
timeBetwRati	Time between two feed ration refreshments	18.00	hours	Cow mastitis	Expert's opinion
averTemp	Average annual temperature	16.45	C	Cow mastitis	World Bank Group
fracFeedDige	Fraction of the feed ration digested	50.00	%	Cow mastitis	Expert's opinion and literature
benContBed	Benchmark contamination level in soil (bedding mat)	7943282.35	CFU/g	Cow mastitis	Literature
preTreatEffi	Pretreatment efficiency % of spores removed	75.00	%	Cow mastitis	Expert's opinion
numMilkDay	Number of milking per day	2.00	NA	Cow mastitis	Expert's opinion
numCowsHerd	Number of cows in the herd	50.00	NA	Cow mastitis	Literature

Figure 6.5. Input data required for the model in Matlab. The user is expected only to modify the yellow section as the code is linked to those cells.

In the second step, the user can make use of two created functions. The first function refers to the cow mastitis model, where Equations 1 to 18 from Chapter 3 are implemented. Then, three outputs can be obtained from it: *S. aureus* load in the bulk tank milk (BTM), the somatic cell count (SCC) in the BTM, and the percentage of annual raw milk losses due to exceeding the *S. aureus* and SCC load. The second function refers to the cow heat stress model and includes Equations 1 and 2 from Chapter 4. Here three outputs are achieved: the monthly THI and the percentage of annual milk losses caused when a month's THI exceeds the cow's threshold, which is previously defined by the user in the spreadsheet.

Once these two steps are carried out, the user is ready to execute the script (i.e., orange box with a black outline in Figure 6.4) and estimate annual raw milk losses from cow mastitis and heat stress. The resulting outputs will be displayed back in the same excel file below the parameters.

7. REFLECTION AND CONCLUSIONS

7.1 REFLECTION OF THE MAIN OUTCOMES

One of the objectives of this thesis is to develop and validate a toolbox to identify and estimate the most significant biophysical impacts of climate change across European dairy farms as well as to estimate the corresponding changes in their environmental performance in a complex and uncertain context.

Despite the inherent uncertainty of climate projections and the complexity of a whole productive sector, this thesis has successfully achieved its objective providing comprehensive information with a scientific basis on the challenges that climate change poses to the European dairy sector by 2050. The developed toolbox has several strengths. It has been transferred into a user-friendly environment so users that may not have specialized knowledge or training can still make use of it. It also provides a list of data sources where the user can get the data required by the toolbox. Another strength is that it is flexible and generic as it can be implemented in any other temporal and geographical horizons as well as in any climate scenario. In order to show its applicability, this thesis has tested it for two contrasting regions by 2050 under several climate scenarios. However, some weaknesses were also identified. One of the main challenges was the scarcity of information or data. For instance, no projections were found on the global market of crop provision by 2050 as further developed in section 7.3. In other cases, it was possible to overcome the limited availability of data or information through the combination and adaptation of available models or tools. For instance, data on raw milk losses is commonly disregarded or not available. As shown in Chapter 3, the integration of RA into LCA in this research supported in the trace and estimation of raw milk losses due to mastitis at the tested dairy farms. Consequently, this integration supports the evaluation of trade-offs between actions driven by food-safety criteria or environmental criteria, enabling the identification of win-win adaptation strategies.

In this research, six climate hazards (i.e., water stress, floodings, crop pest, climate variability, cow heat stress and mastitis) and their biophysical impacts were analysed. Among the six addressed climate hazards, the dairy sector must pay special attention to cow heat stress and mastitis no matter the climate scenario or biogeographical region as they lead to raw milk losses, which have more negative repercussions on the environmental impact than the rest of the climate hazards. Nevertheless, the estimation of the climate hazards, their biophysical impacts, and changes in the environmental performance of the dairy farm have to be done in a landscape full of uncertainties, data gaps, and complexity. Despite this, the proposed toolbox presents specifically tailored tools that allow assessing the impacts of climate change, and the resulting changes in the environmental impact of the dairy sector over two climate scenarios (i.e., SSP2-4.5 and the SSP5-8.5) and four biogeographical regions in which the European dairy sector is concentrated. To avoid the negative impacts of climate change, site-specific adaptation strategies are to be defined and an analysis of their environmental costs needs to be included. But to do so, first an in-depth understanding of the climate hazards and their biophysical impacts is required, which is possible thanks to the toolbox.

There is an urgency to achieve carbon neutrality by reducing GHG emissions and other environmental impacts of the dairy sector and promoting climate resilience production. The proposed toolbox fulfils this urgency, and it serves as a decision support tool for identifying critical climate hazards and establishing efficient resource adaptation strategies while protecting the environment.

7.2 CONTRIBUTION TO EUROPEAN DAIRY SECTOR'S POLICIES AND INDUSTRIAL INITIATIVES

The work behind this thesis has the potential to guide policies and industrial initiatives, thanks to its better understanding of how the European dairy sector will be impacted by climate change by 2050. It can help to strengthen the sector's capacity for adaptation while continuing to minimize its contribution to global warming and other environmental impacts in accordance with the climate and environmental ambitions defined by current European frameworks, such as European Green Deal, and global ones, such as the Paris Agreement and the Sustainable Development Goals. In this context, the Farm to Fork strategy aims to transition to healthy food systems that also protect the environment and climate. The dairy sector stands out in this strategy as a key player, taking into account its significant contribution both to human nutrition and climate change. In addition, the new Common Agricultural Policy emphasizes the implementation of agricultural practices that promote the protection of water, soil, and biodiversity as well as a reduction of GHG emissions. The core of these programs sets a framework to attain carbon neutrality by 2050, and the dairy industry has built a number of climate change mitigation solutions based on this goal. However, the transition of the dairy sector is not only about mitigation but also about adapting to the unavoidable effects of climate change. In this respect, adaptation capacity of the agricultural sector has been a topic recently considered in the European Green Deal, resulting in a series of generic adaptation strategies reported in the “New Strategy on Adaptation to Climate Change”. The European Green Deal recognizes that there is still insufficient knowledge, data, methodologies, and information to underpin climate change impact assessments. So, when it comes to creating adaptive capacity for the dairy sector, there is still a gap that needs to be filled as no specific adaptation strategies for the sector have been identified yet.

Decision-makers must clearly identify and understand the site-specific climate hazards and their biophysical impacts at a local or regional level as the effects of climate change vary across regions in Europe. In this context, this thesis gives the necessary tools to provide an in-depth analysis regarding geographical variations, so information with a scientific basis can be obtained. This research expects to support a wide range of stakeholders involved in the dairy sector at different levels such as associations, companies, and at policy-making level. For instance, thanks to the comprehensive analysis provided, this toolbox can educate members of associations, such as the International Dairy Federation (IDF) and the European Dairy Association (EDA), on the impacts of climate change on the dairy sector. Additionally, policymakers can benefit from this research. Commonly, the environmental cost of adaptation strategies is not fully considered and Chapter 5 highlights win-win adaptation strategies, those that are promising for adapting to climate change at a low environmental cost while ensuring mandatory food safety. In addition, this research is also helpful on a company level. Financial markets need clear, comprehensive, high-quality information on the impacts of climate change and initiatives such as the Task Force on Climate-related Financial Disclosures (TCFD) motivated by the Corporate Sustainability Reporting Directive (CSRD) is a decisive step forward. Its widespread implementation is expected to ensure that the effects of climate change become routinely considered and reported in companies, so they can allocate capital to create adaptive capacity. In this research, the toolbox was tested at a dairy cooperative (i.e., Arla

Foods, Denmark) to provide robust information on the impacts of climate change across its dairy farms in Europe. It was the first exercise of the cooperative to quantify the given impacts, hence a beginning to build the climate resilience of this multinational company. In the way the toolbox supported this cooperative, it can also aid other companies as climate change is already a reality and the CSRD might become mandatory reporting in the coming years.

As a conclusion, the toolbox and information generated in this research provide scientific basis and technical support that can contribute to the achievement of science-based targets for the dairy sector. Achieving science-based targets requires a collaborative effort from all stakeholders in the dairy sector, including farmers, policymakers, researchers, and industry associations.

7.3 FURTHER RESEARCH

The proposed toolbox allows to understand better the impacts of climate change on the European dairy sector, and from there, it allows to better design of site-specific adaptation strategies. However, the lack of information can lead to imprecise results in the toolbox. Thus, in order to improve the utility of the toolbox, further research needs to be done. For instance, there are no projections of the climate change consequences on the trading of agricultural commodities by 2050. In view of the lack of this information by 2050, this research assumed the same crops used by the dairy farms and their origins from the baseline scenarios (i.e., 2020). Nevertheless, this is not correct as the markets and the availability of crops in the future will be affected by climate change and by unexpected non-climate related factors (e.g., wars and pandemics). An incorrect definition of the crops and their origin used by dairy farms in 2050 can lead to a wrong definition of changes in the background data at the dairy farm stage. For example, some countries will have increases in crop yields, while other countries will have decreases.

Climate change projections are inherently uncertain. This uncertainty can make it challenging to accurately predict the specific biophysical impacts of climate hazards on the dairy sector. In the context of this research, uncertainty arises from a range of sources, including climate scenarios, climate models, natural variability and implemented mathematical models. This means that the toolbox can provide valuable insights into the potential future challenges that the dairy sector might expect, but the incorporation of uncertainty analysis can be promising. It is important to acknowledge and account for this uncertainty when developing tools and models for climate change adaptation, including those developed for the dairy sector. By doing so, stakeholders in the sector can make more informed decisions and develop more effective strategies for adapting to the potential impacts of climate change.

REFERENCES

- ADB. (2021). Input-Output Tables for Asia and the Pacific (Asian Development Bank). <https://www.adb.org/what-we-do/data/regional-input-output-tables>
- AgriAdapt. (2017). Sustainable adaptation of typical EU farming systems to climate change. A1: Baseline reports for the 4 main EU Climate Risk Regions.
- Ahmed, E., Fukuma, N., Hanada, M., & Nishida, T. (2021). Insects as novel ruminant feed and a potential mitigation strategy for methane emissions. *Animals*, 11(9), 1–13. <https://doi.org/10.3390/ani11092648>
- Alexandratos, N. and J. B. (2012). World Agriculture Towards 2030/2050. The 2012 Revision. In ESA Working paper No. 12-03 (Vol. 12, Issue 12).
- Amamou, H., Sassi, M. Ben, Aouadi, H., Khemiri, H., Mahouachi, M., Beckers, Y., & Hammami, H. (2018). Climate change-related risks and adaptation strategies as perceived in dairy cattle farming systems in Tunisia. *Climate Risk Management*, 20(March 2017), 38–49. <https://doi.org/10.1016/j.crm.2018.03.004>
- Antonyan, M., & Hoekstra, A. Y. (2019). Energy Footprint of Water Desalination (Issue June).
- Arla Foods. (2022a). Annual Report 2022. Financial and Sustainability.
- Arla Foods. (2022b). Data Driven Dairy. How climate checks are driving action to reduce emissions on Arla Farms.
- Baranyi, J., & Roberts, T. (1994). A dynamic approach to predicting bacterial growth in food. *International Journal of Food Microbiology*, 23, 277–294.
- Baumann, H., & Tillman, A. M. (2004). *The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application* (Professional Publishing House (ed.); 3rd ed.).
- Black, R. A., Taraba, J. L., Day, G. B., Damasceno, F. A., Newman, M. C., Akers, K. A., Wood, C. L., McQuerry, K. J., & Bewley, J. M. (2014). The relationship between compost bedded pack performance, management, and bacterial counts. *Journal of Dairy Science*, 97(5), 2669–2679. <https://doi.org/10.3168/jds.2013-6779>
- Boadi, D., Benchaar, C., Chiquette, J., & Massé, D. (2004). Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Canadian Journal of Animal Science*, 84(3), 319–335. <https://doi.org/10.4141/A03-109>
- Boonkum, W., Misztal, I., Duangjinda, M., Pattarajinda, V., Tumwasorn, S., & Sanpote, J. (2011). Genetic effects of heat stress on milk yield of Thai Holstein crossbreds. *Journal of Dairy Science*, 94(1), 487–492. <https://doi.org/10.3168/jds.2010-3421>
- Bórawski, P., Pawlewicz, A., Parzonko, A., Harper, J. K., & Holden, L. (2020). Factors shaping cow's milk production in the EU. *Sustainability (Switzerland)*, 12(1), 1–15. <https://doi.org/10.3390/SU12010420>
- Borreani, G., & Tabacco, E. (2010). The relationship of silage temperature with the microbiological status of the face of corn silage bunkers. *Journal of Dairy Science*, 93(6), 2620–2629. <https://doi.org/10.3168/jds.2009-2919>

- Bradley, A. J., Leach, K. A., Green, M. J., Gibbons, J., Ohnstad, I. C., Black, D. H., Payne, B., Prout, V. E., & Breen, J. E. (2018). The impact of dairy cows' bedding material and its microbial content on the quality and safety of milk – A cross sectional study of UK farms. *International Journal of Food Microbiology*, 269(April 2017), 36–45. <https://doi.org/10.1016/j.ijfoodmicro.2017.12.022>
- Breyne, K., Honaker, R. W., Hobbs, Z., Richter, M., Zaczek, M., Spangler, T., Steenbrugge, J., Lu, R., Kinkhabwala, A., Marchon, B., Meyer, E., & Mokres, L. (2017). Efficacy and safety of a Bovine-Associated *Staphylococcus aureus* Phage Cocktail in a murine model of mastitis. *Frontiers in Microbiology*, 8(NOV), 1–11. <https://doi.org/10.3389/fmicb.2017.02348>
- Bruckner, M., Wood, R., Moran, D., Kuschnig, N., Wieland, H., Maus, V., & Börner, J. (2019). FABIO - The Construction of the Food and Agriculture Biomass Input-Output Model. *Environmental Science and Technology*, 53(19), 11302–11312. <https://doi.org/10.1021/acs.est.9b03554>
- Calvo, M. N. (2022). Agroforestry as an approach to reduce the water footprint in a profitable way in the Maule Region, Chile.
- Calzadilla, A., Rehdanz, K., Betts, R., Falloon, P., Wiltshire, A., & Tol, R. S. J. (2013). Climate change impacts on global agriculture. *Climatic Change*, 120(1–2), 357–374. <https://doi.org/10.1007/s10584-013-0822-4>
- Carmona-Moreno, C., Dondeynaz, C., & Biedler, M. (2019). Position Paper on Water, Energy, Food, and Ecosystem (WEFE) Nexus and Sustainable development Goals (SDGs). <https://doi.org/10.2760/5295>
- Carozzi, M., Martin, R., Klumpp, K., & Massad, R. S. (2022). Effects of climate change in European croplands and grasslands: Productivity, greenhouse gas balance and soil carbon storage. *Biogeosciences*, 19(12), 3021–3050. <https://doi.org/10.5194/bg-19-3021-2022>
- CESFAC. (2007). Guía para el desarrollo de normas de Higienización de Piensos.
- Ciscar, J. C., Feyen, L., Ibarreta, D., & Soria, A. (2018). Climate impacts in Europe: Final report of the JRC PESETA III project. <https://doi.org/10.2760/93257>
- Climalait. (2021). CLIMALAIT: Adapting to climate change for resilient French dairy farms. <https://idele.fr/climalait/>
- ClimateADAPT. (2023). The Adaptation Support Tool – Getting started. <https://climate-adapt.eea.europa.eu/en/knowledge/tools/adaptation-support-tool>
- Codex Alimentarius Commission. (1999). Principles and Guidelines for the Conduct of Microbiological Risk Assessment.
- Coffey, R., Cummins, E., & Ward, S. (2009). Exposure assessment of mycotoxins in dairy milk. *Food Control*, 20(3), 239–249. <https://doi.org/10.1016/j.foodcont.2008.05.011>
- Colombani, N., Osti, A., Volta, G., & Mastroicco, M. (2016). Impact of Climate Change on Salinization of Coastal Water Resources. *Water Resources Management*, 30(7), 2483–2496. <https://doi.org/10.1007/s11269-016-1292-z>
- Cortés, A., Feijoo, G., Fernández, M., & Moreira, M. T. (2020). Pursuing the route to eco-

- efficiency in dairy production: The case of Galician area. *Journal of Cleaner Production*, 124861. <https://doi.org/10.1016/j.jclepro.2020.124861>
- Cymbalsky, J. (2015). Energy Conservation Program: Energy Conservation Standards for Pump.
- De Vries, M. (2018). Vulnerability and adaptation strategies of dairy farming systems to extreme climate events in southwest Uganda. In Wageningen Livestock Research, Wageningen.
- Dhankher, O. P., & Foyer, C. H. (2018). Climate resilient crops for improving global food security and safety. *Plant Cell and Environment*, 41(5), 877–884. <https://doi.org/10.1111/pce.13207>
- Dijkman, T. J., Basset-Mens, C., Antón, A., & Núñez, M. (2018). LCA of Food and Agriculture BT - Life Cycle Assessment: Theory and Practice (Michael Z Hauschild, R. K. Rosenbaum, & S. I. Olsen (eds.); pp. 723–754). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_29
- Dikmen, S., Khan, F. A., Huson, H. J., Sonstegard, T. S., Moss, J. I., Dahl, G. E., & Hansen, P. J. (2014). The SLICK hair locus derived from Senepol cattle confers thermotolerance to intensively managed lactating Holstein cows. *Journal of Dairy Science*, 97(9), 5508–5520. <https://doi.org/10.3168/jds.2014-8087>
- Djekic, I., Miocinovic, J., Tomasevic, I., Smigic, N., & Tomic, N. (2014). Environmental life-cycle assessment of various dairy products. *Journal of Cleaner Production*, 68, 64–72. <https://doi.org/10.1016/j.jclepro.2013.12.054>
- Driehuis, F., Spanjer, M. C., Scholten, J. M., & Te Giffel, M. C. (2008). Occurrence of mycotoxins in feedstuffs of dairy cows and estimation of total dietary intakes. *Journal of Dairy Science*, 91(11), 4261–4271. <https://doi.org/10.3168/jds.2008-1093>
- EC. (2013). An EU Strategy on adaptation to climate change. In COM(2013) 216 final. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0216>
- EC. (2016). EU Reference Scenario 2016. Presentation.
- EC. (2021). A European Green Deal Striving to be the first climate-neutral continent.
- EC. (2022). Corporate sustainability reporting (European Commission). https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en
- Eccles, K. M., Pauli, B. D., & Chan, H. M. (2019). The Use of Geographic Information Systems for Spatial Ecological Risk Assessments: An Example from the Athabasca Oil Sands Area in Canada. *Environmental Toxicology and Chemistry*, 38(12), 2797–2810. <https://doi.org/10.1002/etc.4577>
- Ecoinvent. (2020). ecoinvent version 3.7. <https://ecoinvent.org/>
- EDA. (2018a). Product Environmental Footprint Category Rules for Dairy Products.
- EDA. (2018b). The European Dairy Sector & the Sustainable Development Goals (SDGs).
- EDA. (2019). The Dairy sector & the Green Deal (Issue December).

- EEA. (2014). Projected changes in heavy precipitation in winter and summer. European Environment Agency (EEA). https://www.eea.europa.eu/data-and-maps/figures#c0=15&c5=&c15=all&b_start=0
- EEA. (2017). Climate change, impacts and vulnerability in Europe 2016. An indicator based report (European Environment Agency (EEA) (ed.); Issue 1). <https://www.eea.europa.eu/publications/climate-change-adaptation-and-disaster>
- EEA. (2019). Climate change adaptation in the agriculture sector in Europe. In EEA Report (Issue 04/2019).
- EFSA. (2020). Climate change as a driver of emerging risks for food and feed safety, plant, animal health and nutritional quality. In EFSA Supporting Publications (Vol. 17, Issue 6). <https://doi.org/10.2903/sp.efsa.2020.en-1881>
- Egas, D., Ponsá, S., & Colon, J. (2020). CalcPEFDairy: A Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products. *Journal of Environmental Management*, 260(April 2019). <https://doi.org/10.1016/j.jenvman.2019.110049>
- EPD. (2021). The international EPD System - Environmental Product Declarations.
- ESRI. (2022). Environmental Systems Research Institute. <https://www.esri.com/en-us/home>
- EStat. (2019). Input-Output Tables for Japan. <https://www.e-stat.go.jp/en/stat-search/files?page=1&toukei=00200603>
- European Commission. (2003). Opinion of the Scientific Committee on veterinary measures relating to public health on Staphylococcal enterotoxins in milk products, particularly cheeses.
- European Commission. (2004). Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for food of animal origin.
- European Commission. (2012). Product Environmental Footprint (PEF) Guide.
- European Commission. (2019). COMMISSION DELEGATED REGULATION (EU) 2019/1702 of 1 August 2019 supplementing Regulation (EU) 2016/2031 of the European Parliament and of the Council by establishing the list of priority pests. *Official Journal of the European Union*, 260(December), 10–12.
- European Commission. (2021). Farm to Fork Strategy For a fair, healthy and environmentally-friendly food system (Issue DG SANTE/Unit 'Food information and composition, food waste').
- European Dairy Association. (2018). Product Environmental Footprint Category Rules for Dairy Products.
- European Dairy Association. (2019). The Dairy sector & the Green Deal (Issue December).
- European Food Safety Authority. (2009). Scientific report on the effects of farming systems on dairy cow welfare and disease. Report of the Panel on Animal Health and Welfare. *EFSA Journal*, 1143, 152–284.

- European Food Safety Authority. (2020). Climate change as a driver of emerging risks for food and feed safety, plant, animal health and nutritional quality. In EFSA Supporting Publications (Vol. 17, Issue 6). <https://doi.org/10.2903/sp.efsa.2020.en-1881>
- Eurostat. (2021). Milk and milk product statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics#Milk_production
- Eurostat. (2022). Cows' milk collection and products obtained - annual data. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_mk_cola&lang=en
- Fanzo, J., Davis, C., McLaren, R., & Choufani, J. (2018). The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security*, 18(January), 12–19. <https://doi.org/10.1016/j.gfs.2018.06.001>
- FAO. (2007). Adaptation to climate change in agriculture , forestry and fisheries : Perspective , framework and. Interdepartmental Working Group on Climate Change, 32pp. <ftp://ftp.fao.org/docrep/fao/009/j9271e/j9271e.pdf> http://www.fao.org/NR/climpag/index_fr.asp
- FAO. (2022). Calculation procedures AquaCrop Reference manual.
- FAO and GDP. (2018). Climate change and the global dairy cattle sector – The role of the dairy sector in a low-carbon future.
- FAO and WHO. (2006). Food safety risk analysis: A guide for national food safety authorities. In FAO Food and Nutrition Paper 87. World Health Organization.
- FAOSTAT. (2022). Food and agriculture data. <https://www.fao.org/faostat/en/#home>
- Feliciano, R. J., Guzmán-Luna, P., Boué, G., Mauricio-Iglesias, M., Hospido, A., & Membré, J. (2022). Strategies to mitigate food safety risk while minimizing environmental impacts in the era of climate change. *Trends in Food Science & Technology*, In press.
- Feliciano, R. J., Guzmán-Luna, P., Hospido, A., & Membré, J. M. (2023). Evaluation of food safety and environmental impacts of risk mitigation strategies by applying multi-criteria decision analysis technique: a large dairy farm as case-study. Manuscript in Preparation.
- FENIL. (2022). Producción del sector lácteo. Federación Nacional de Industrias Lácteas (FENIL). <https://fenil.org/produccion-sector-lacteo/>
- Fodor, N., Foskolos, A., Topp, C. F. E., Moorby, J. M., Pásztor, L., & Foyer, C. H. (2018). Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. *PLoS ONE*, 13(5), 1–18. <https://doi.org/10.1371/journal.pone.0197076>
- Food and Agriculture Organization of the United Nations. (2021). Global Action for Fall Armyworm Control. <https://www.fao.org/fall-armyworm/monitoring-tools/faw-map/en/>
- FSB. (2022). Task Force on Climate-related Financial Disclosures. 2022 Status report.
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falucci, A., & Tempio, G. (2013). Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities (Vol. 14, Issue 2).
- Gerber, P. J., Vellinga, T., Opio, C., Henderson, B., & Steinfeld, H. (2010). Greenhouse Gas

- Emissions from the Dairy Sector. Africa, 98. [https://doi.org/10.1016/S0301-4215\(01\)00105-7](https://doi.org/10.1016/S0301-4215(01)00105-7)
- Ghanbari, S., Eastin, I. L., & Khalyani, J. H. (2021). Ecosystem-based Adaptation (EbA) strategies for reducing climate change risks Seite 349 138. 349–373.
- Gilioli, G., Sperandio, G., Simonetto, A., Ciampitti, M., & Gervasio, P. (2022). Assessing the risk of establishment and transient populations of *Spodoptera frugiperda* in Europe. *Journal of Pest Science*. <https://doi.org/10.1007/s10340-022-01517-0>
- Global Methane Pledge. (2021). Global Methane Pledge. Climate & Clean Air Coalition Secretariat. <https://www.globalmethanepledge.org/>
- Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2009). ReCiPe 2008. Potentials, 1–44. http://www.pre-sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf
- Gonçalves, J. L., Kamphuis, C., Martins, C. M. M. R., Barreiro, J. R., Tomazi, T., Gameiro, A. H., Hogeveen, H., & dos Santos, M. V. (2018). Bovine subclinical mastitis reduces milk yield and economic return. *Livestock Science*, 210(June 2017), 25–32. <https://doi.org/10.1016/j.livsci.2018.01.016>
- Grigoriadis, V., Nugent, A., & Brereton, P. (2021). Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends in Food Science and Technology*, 112(March), 298–311. <https://doi.org/10.1016/j.tifs.2021.03.047>
- Guinée, J. B., Heijungs, R., Vijver, M. G., & Peijnenburg, W. J. G. M. (2017). Setting the stage for debating the roles of risk assessment and life-cycle assessment of engineered nanomaterials. *Nature Nanotechnology*, 12(8), 727–733. <https://doi.org/10.1038/NNANO.2017.135>
- Guo, M., Gao, Y., Xue, Y., Liu, Y., Zeng, X., Cheng, Y., Ma, J., Wang, H., Sun, J., Wang, Z., & Yan, Y. (2021). Bacteriophage Cocktails Protect Dairy Cows Against Mastitis Caused By Drug Resistant *Escherichia coli* Infection. *Frontiers in Cellular and Infection Microbiology*, 11(June), 1–11. <https://doi.org/10.3389/fcimb.2021.690377>
- Guo, X., Akram, S., Stedtfeld, R., Johnson, M., Chabrelie, A., Yin, D., & Mitchell, J. (2021). Distribution of antimicrobial resistance across the overall environment of dairy farms – A case study. *Science of the Total Environment*, 788, 147489. <https://doi.org/10.1016/j.scitotenv.2021.147489>
- Gutiérrez, D., Fernández, L., Rodríguez, A., & García, P. (2019). Role of Bacteriophages in the Implementation of a Sustainable Dairy Chain. 10(January), 1–14. <https://doi.org/10.3389/fmicb.2019.00012>
- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2021). Analysing the interaction between the dairy sector and climate change from a life cycle perspective: A review. *Trends in Food Science and Technology*, 126(168–179). <https://doi.org/10.1016/j.tifs.2021.09.001>
- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2023a). A toolbox to estimate variations on dairy farms' environmental impact due to climate change at different temporal and geographical horizons (under submission). *Journal of Cleaner*

Production.

- Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., & Hospido, A. (2023b). Evaluating win-win site-specific dairy farm adaptation strategies to climate change by 2050 (To be submitted). *Sustainable Production and Consumption*.
- Guzmán-Luna, P., Nag, R., Martínez, I., Mauricio-Iglesias, M., Hospido, A., & Cummis, E. (2022). Quantifying current and future raw milk losses due to bovine mastitis on European dairy farms under climate change scenarios. *Science of the Total Environment*, 833(155–149). <https://doi.org/10.1016/j.scitotenv.2022.155149>
- Halasa, T., Huijps, K., Østerås, O., & Hogeveen, H. (2007). Economic effects of bovine mastitis and mastitis management: A review. *Veterinary Quarterly*, 29(1), 18–31. <https://doi.org/10.1080/01652176.2007.9695224>
- Halmemies-Beauchet-Filleau, A., Rinne, M., Lamminen, M., Mapato, C., Ampapon, T., Wanapat, M., & Vanhatalo, A. (2018). Review: Alternative and novel feeds for ruminants: Nutritive value, product quality and environmental aspects. *Animal*, 12(s2), S295–S309. <https://doi.org/10.1017/S1751731118002252>
- Hansen, P. J. (2020). Prospects for gene introgression or gene editing as a strategy for reduction of the impact of heat stress on production and reproduction in cattle. In *Theriogenology* (Vol. 154). Elsevier Inc. <https://doi.org/10.1016/j.theriogenology.2020.05.010>
- Hauschild, M.Z., & Huijbregts, M. A. J. (2015). *Life Cycle Assessment* (Springer (ed.); 2015th ed.).
- Heikkilä, A. M., Liski, E., Pyörälä, S., & Taponen, S. (2018). Pathogen-specific production losses in bovine mastitis. *Journal of Dairy Science*, 101(10), 9493–9504. <https://doi.org/10.3168/jds.2018-14824>
- Hempel, S., Menz, C., Pinto, S., Galán, E., Janke, D., Estellés, F., Müschner-Siemens, T., Wang, X., Heinicke, J., Zhang, G., Amon, B., Del Prado, A., & Amon, T. (2019). Heat stress risk in European dairy cattle husbandry under different climate change scenarios-uncertainties and potential impacts. *Earth System Dynamics*, 10(4), 859–884. <https://doi.org/10.5194/esd-10-859-2019>
- Herzog, A., Winckler, C., Hörtenhuber, S., & Zollitsch, W. (2021). Environmental impacts of implementing basket fans for heat abatement in dairy farms. *Animal*, 15(7), 100274. <https://doi.org/10.1016/j.animal.2021.100274>
- Hoekstra, A. Y., & Mekonnen, M. M. (2010). The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. Volume 1 : Main Report. Value of Water Research Report Series No. 47, 1(16), 80. <http://wfn.project-platforms.com/Reports/Report47-WaterFootprintCrops-Vol1.pdf>
- Hofste, R. W., Kuzma, S., Walker, S., Sutanudjaja, E. H., Bierkens, M. F. P., Kuijper, M. J. M., Sanchez, M. F., Beek, R. V. A. N., Wada, Y., Galvis, S., & Reig, P. (2019). Technical Note Aqueduct 3 . 0 : Updated Decision-Relevant Global Water Risk Indicators. World Resources Institute, July, 1–53.
- Hogan, J. S., Smith, K. L., Todhunter, D. A., & Schoenberger, P. S. (1990). Bacterial Counts Associated with Recycled Newspaper Bedding. *Journal of Dairy Science*, 73(7), 1756–

1761. [https://doi.org/10.3168/jds.S0022-0302\(90\)78853-4](https://doi.org/10.3168/jds.S0022-0302(90)78853-4)

- Hope, J., Klein, G., Mclauchlin, J., Messens, W., Muller-, C., Nguyen-the, C., Noerrung, B., Peixe, L., Maradona, M. P., Sofos, J., Threlfall, E. J., Vågsholm, I., & Vanopdenbosch, E. (2009). Food safety aspects of dairy cow housing and husbandry systems 1 Scientific Opinion of the Panel on Biological Hazards Adopted on 9 July 2009. July, 1–27.
- Hospido, A., & Sonesson, U. (2005). The environmental impact of mastitis: A case study of dairy herds. *Science of the Total Environment*, 343(1–3), 71–82. <https://doi.org/10.1016/j.scitotenv.2004.10.006>
- Houben, E. H. P., Dijkhuizen, A. A., Van Arendonk, J. A. M., & Huirne, R. B. M. (1993). Short- and Long-Term Production Losses and Repeatability of Clinical Mastitis in Dairy Cattle. *Journal of Dairy Science*, 76(9), 2561–2578. [https://doi.org/10.3168/jds.S0022-0302\(93\)77591-8](https://doi.org/10.3168/jds.S0022-0302(93)77591-8)
- Hristov, J., Toreti, A., Pérez, I., Dentener, F., Fellmann, T., Elleby, C., Ceglar, A., Fumagalli, D., Niemeyer, S., Cerrani, I., Panarello, L., & Bratu, M. (2020). Analysis of climate change impacts on EU agriculture by 2050. <https://doi.org/10.2760/121115>
- Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., M.D.M., V., Hollander, A., & Van-Zelm, R. (2017). ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. In RIVM Report 2016-0104. www.rivm.nl/en
- IDF. (2015). A common carbon footprint approach for the dairy sector. The IDF guide to standard life cycle assessment methodology (Vol. 482).
- IDF. (2017). The IDF Guide to Water Footprint Methodology for the Dairy Sector. [https://doi.org/10.1016/S0958-6946\(97\)88755-9](https://doi.org/10.1016/S0958-6946(97)88755-9)
- IDF. (2018). Animal Health Report. Issue N°12 (Issue September).
- Idrissou, Y., Assani, A. S., Baco, M. N., Yabi, A. J., & Alkoiret Traoré, I. (2020). Adaptation strategies of cattle farmers in the dry and sub-humid tropical zones of Benin in the context of climate change. *Heliyon*, 6(7). <https://doi.org/10.1016/j.heliyon.2020.e04373>
- IEA. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. In International Energy Agency. <https://www.iea.org/reports/net-zero-by-2050>
- INE. (2019). Tablas input output 2016 (Instituto Nacional de Estadística). https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736177058&menu=resultados&idp=1254735576581
- Ingalls, W. (2001). Somatic cells: Function and relation to milk quality. http://www.milkproduction.com/%0ALibrary/Articles/Somatic_Cells_Function_and_Relationship_t%0Ao_Milk_Product ion.htm
- IPCC. (1994). Climate Change Impacts and Adaptations: IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. CGER-I015-'94. In Intergovernmental Panel on Climate Change (p. 59 pp.).
- IPCC. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working

Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker,., <https://doi.org/10.1260/095830507781076194>

- IPCC. (2014a). Climate Change 2014: impacts, adaptation, and vulnerability. part A: global and sectoral aspects. In Climate Change 2014: Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. <https://doi.org/10.1017/CBO9781107415386>
- IPCC. (2014b). Climate Change 2014: Synthesis Report. [https://doi.org/10.1016/S0022-0248\(00\)00575-3](https://doi.org/10.1016/S0022-0248(00)00575-3)
- IPCC. (2021). Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. In Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Issue Cambridge University Press. In Press). <https://doi.org/10.1080/03736245.2010.480842>
- IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- IRENA. (2020). Global Renewables Outlook: Energy transformation 2050. In International Renewable Energy Agency. <https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020>
- ISO 14040. (2006). Environmental management — Life cycle assessment — Principles and framework.
- ISO 14044. (2006). Environmental management — Life cycle assessment — Requirements and guidelines.
- ISO 14046. (2014). Environmental management — Water footprint — Principles, requirements and guidelines.
- ISO 14067. (2018). Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.
- Jayarao, B. M., Pillai, S. R., Sawant, A. A., Wolfgang, D. R., & Hegde, N. V. (2004). Guidelines for monitoring bulk tank milk somatic cell and bacterial counts. *Journal of Dairy Science*, 87(10), 3561–3573. [https://doi.org/10.3168/jds.S0022-0302\(04\)73493-1](https://doi.org/10.3168/jds.S0022-0302(04)73493-1)
- Jingar, S. C., Mehla, R. K., & Singh, M. (2014). Climatic effects on occurrence of clinical mastitis in different breeds of cows and buffaloes. 848–853. [https://doi.org/10.3168/jds.S0022-0302\(88\)79626-5](https://doi.org/10.3168/jds.S0022-0302(88)79626-5)
- Kalaugher, E., Bornman, J. F., Clark, A., & Beukes, P. (2013). An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system. *Environmental Modelling and Software*, 39, 176–187. <https://doi.org/10.1016/j.envsoft.2012.03.018>
- Kateřina, B., Marcela, V.-K., Vladimír, B., Libor, K., Ivana, K., & Renáta, K. (2016). Microbiological quality of raw milk in the Czech Republic. *Czech Journal of Food Sciences*, 34(No. 3), 189–196. <https://doi.org/10.17221/25/2016-cjfs>

- Key, N., & Sneeringer, S. (2014). Potential effects of climate change on the productivity of U.S. dairies. *American Journal of Agricultural Economics*, 96(4), 1136–1156. <https://doi.org/10.1093/ajae/aau002>
- Kondrup, C., Mercogliano, P., Bosello, F., Mysiak, J., Scoccimarro, E., Rizzo, A., Ebrey, R., de Ruiter, M., Jeuken, A., & Watkiss, P. (2022). *Climate Adaptation Modelling*. In Springer Climate. https://doi.org/10.1007/978-3-030-86211-4_24
- Krizsan, S. J., Chagas, J. C., Pang, D., & Cabezas-Garcia, E. H. (2021). Sustainability aspects of milk production in Sweden. *Grass and Forage Science*, 76(2), 205–214. <https://doi.org/10.1111/gfs.12539>
- Lassey, K. R. (2007). Livestock methane emission: From the individual grazing animal through national inventories to the global methane cycle. *Agricultural and Forest Meteorology*, 142(2–4), 120–132. <https://doi.org/10.1016/j.agrformet.2006.03.028>
- Le Riche, E. L., VanderZaag, A. C., Burt, S., Lapen, D. R., & Gordon, R. (2017). Water use and conservation on a free-stall dairy farm. *Water (Switzerland)*, 9(12), 1–14. <https://doi.org/10.3390/w9120977>
- Leão, S., Roux, P., Loiseau, E., Junqua, G., Sferratore, A., Penru, Y., & Rosenbaum, R. K. (2019). Prospective Water Supply Mix for Life Cycle Assessment and Resource Policy Support-Assessment of Forecasting Scenarios Accounting for Future Changes in Water Demand and Availability. *Environmental Science and Technology*, 53(3), 1374–1384. <https://doi.org/10.1021/acs.est.8b04071>
- Leão, S., Roux, P., Núñez, M., Loiseau, E., Junqua, G., Sferratore, A., Penru, Y., & Rosenbaum, R. K. (2018). A worldwide-regionalised water supply mix (WSmix) for life cycle inventory of water use. *Journal of Cleaner Production*, 172, 302–313. <https://doi.org/10.1016/j.jclepro.2017.10.135>
- Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E. M., Brunner, L., Knutti, R., & Hawkins, E. (2020). Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics*, 11(2), 491–508. <https://doi.org/10.5194/esd-11-491-2020>
- Lenzen, M., & Crawford, R. (2009). The Path Exchange Method for Hybrid LCA. *Environmental Science & Technology*, 43(21), 8251–8256. <https://doi.org/10.1021/es902090z>
- Leso, L., Barbari, M., Lopes, M. A., Damasceno, F. A., Galama, P., Taraba, J. L., & Kuipers, A. (2020). Invited review: Compost-bedded pack barns for dairy cows. *Journal of Dairy Science*, 103(2), 1072–1099. <https://doi.org/10.3168/jds.2019-16864>
- LIFE. (2021). Agroforestry systems for climate change adaptation of Mediterranean agricultural and forest areas. <https://agroforadapt.eu/en/home-eng/>
- Mahaut, L., Pironon, S., Barnagaud, J. Y., Bretagnolle, F., Khoury, C. K., Mehrabi, Z., Milla, R., Phillips, C., Rieseberg, L. H., Violle, C., & Renard, D. (2022). Matches and mismatches between the global distribution of major food crops and climate suitability. *Proceedings of the Royal Society B: Biological Sciences*, 289(1983). <https://doi.org/10.1098/rspb.2022.1542>

- Malek dos Reis, C. B., Barreiro, J. R., Mestieri, L., Porcionato, M. A. de F., & dos Santos, M. V. (2013). Effect of somatic cell count and mastitis pathogens on milk composition in Gyr cows. *BMC Veterinary Research*, 9. <https://doi.org/10.1186/1746-6148-9-67>
- Malliaroudaki, M. I., Watson, N., Ferrari, R., Nchari, L. N., & Gomes, R. L. (2021). Towards net-zero energy in the dairy industry: The role of supply chain modelling to address climate change. *Trends in Food Science and Technology*.
- Malliaroudaki, M. I., Watson, N. J., Ferrari, R., Nchari, L. N., & Gomes, R. L. (2022). Energy management for a net zero dairy supply chain under climate change. *Trends in Food Science and Technology*, 126, 153–167. <https://doi.org/10.1016/j.tifs.2022.01.015>
- MAPA. (2022). Informe de coyuntura del sector vacuno de leche. <https://cpage.mpr.gob.es/NIPO:003191193>
- Mazzetto, A., Falconer, S., & Ledgard, S. (2021). Mapping the carbon footprint of milk for dairy cows. Report Dairy NZ, February. <https://ucanr.edu/sites/progamteams/files/347129.pdf>
- Medveov, A., & Valk, ubomr. (2012). Staphylococcus aureus: Characterisation and Quantitative Growth Description in Milk and Artisanal Raw Milk Cheese Production. Structure and Function of Food Engineering. <https://doi.org/10.5772/48175>
- Mekonnen, S. A., Lam, T. J. G. M., Hoekstra, J., Rutten, V. P. M. G., Tessema, T. S., Broens, E. M., Riesebo, A. E., Spaninks, M. P., & Koop, G. (2018). Characterization of Staphylococcus aureus isolated from milk samples of dairy cows in small holder farms of North-Western Ethiopia. *BMC Veterinary Research*, 14(1), 1–8. <https://doi.org/10.1186/s12917-018-1558-1>
- Misiou, O., & Koutsoumanis, K. (2021). Climate change and its implications for food safety and spoilage. *Trends in Food Science and Technology*, 126(December 2020), 142–152.
- Mitchel, J., Weir, M. H., & Rose, J. (2021). Quantitative Microbial Risk Assessment. <http://qmrawiki.org/>
- More, S. J., Clegg, T. A., Lynch, P. J., & O’Grady, L. (2013). The effect of somatic cell count data adjustment and interpretation, as outlined in european union legislation, on herd eligibility to supply raw milk for processing of dairy products. *Journal of Dairy Science*, 96(6), 3671–3681. <https://doi.org/10.3168/jds.2012-6182>
- Mostert, P. F., Bokkers, E. A. M., de Boer, I. J. M., & van Middelaar, C. E. (2019). Estimating the impact of clinical mastitis in dairy cows on greenhouse gas emissions using a dynamic stochastic simulation model: a case study. *Animal*, 13(12), 2913–2921. <https://doi.org/10.1017/S1751731119001393>
- Myllys, V., & Rautala, H. (1995). Characterization of Clinical Mastitis in Primiparous Heifers. *Journal of Dairy Science*, 78(3), 538–545. [https://doi.org/10.3168/jds.S0022-0302\(95\)76664-4](https://doi.org/10.3168/jds.S0022-0302(95)76664-4)
- Naito, H., Ogawa, Y., Kubota, A., & Kondo, N. (2013). Measurement of somatic cell count in Cow’s raw milk for detecting mastitis by using attenuated total reflection terahertz spectroscopy. In *IFAC Proceedings Volumes (IFAC-PapersOnline) (Vol. 4, Issue PART 1)*. IFAC. <https://doi.org/10.3182/20130828-2-SF-3019.00040>

- Nakamura, S., & Nansai, K. (2016). Input–Output and Hybrid LCA BT - Special Types of Life Cycle Assessment (M. Finkbeiner (ed.); pp. 219–291). Springer Netherlands. https://doi.org/10.1007/978-94-017-7610-3_6
- Nalon, E., & Stevenson, P. (2019). Protection of dairy cattle in the EU: State of play and directions for policymaking from a legal and animal advocacy perspective. *Animals*, 9(12). <https://doi.org/10.3390/ani9121066>
- NASA. (2021). The POWER Project. NASA Prediction Of Worldwide Energy Resources. <https://power.larc.nasa.gov/>
- Nkomwa, E. C., Joshua, M. K., Ngongondo, C., Monjerezi, M., & Chipungu, F. (2014). Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: A case study of Chagaka Village, Chikhwawa, Southern Malawi. *Physics and Chemistry of the Earth*, 67–69, 164–172. <https://doi.org/10.1016/j.pce.2013.10.002>
- Notarnicola, B., Tassielli, G., Renzulli, P. A., Castellani, V., & Sala, S. (2017). Environmental impacts of food consumption in Europe. *Journal of Cleaner Production*, 140, 753–765. <https://doi.org/10.1016/j.jclepro.2016.06.080>
- Noya, I., González-García, S., Berzosa, J., Baucells, F., Feijoo, G., & Moreira, M. T. (2018). Environmental and water sustainability of milk production in Northeast Spain. *Science of the Total Environment*, 616–617, 1317–1329. <https://doi.org/10.1016/j.scitotenv.2017.10.186>
- Noyes, N. R., Slizovskiy, I. B., & Singer, R. S. (2021). Beyond Antimicrobial Use: A Framework for Prioritizing Antimicrobial Resistance Interventions. *Annual Review of Animal Biosciences*, 9(1), 313–332. <https://doi.org/10.1146/annurev-animal-072020-080638>
- NRC. (1971). A guide to environmental research on animals.
- O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42, 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>
- OECD/FAO. (2020). OECD-FAO Agricultural Outlook 2020-2029. In OECD Publishing Paris, /Food and Agriculture Organization of the United Nations, Rome. https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2020-2029_1112c23b-en
- Olivier, J. G. J., Janssens-Maenhout, G., Muntean, M., & Peters, J. A. H. W. (2016). Trends in Global CO2 Emissions: 2016 Report. PBL Netherlands Environmental Assessment Agency: The Hague. PBL Netherlands Environmental Assessment Agency & European Commission's Joint Research Centre (JRC), 86.
- Optibarn. (2017). Optibarn - Optimised animal specific barn climatisation facing temperature rise and increased climate variability. <https://optibarn.atb-potsdam.de/en/project>
- Pantoja, J. C. F., Reinemann, D., & Ruegg, P. L. (2009). Associations among milk quality indicators in raw bulk milk. *Journal of Dairy Science*, 92(10), 4978–4987. <https://doi.org/10.3168/jds.2009-2329>

- PCR. (2013). Raw milk. Product group: UN CPC 022.
- Peters, K., Breitsameter, L., & Gerowitt, B. (2014). Impact of climate change on weeds in agriculture: A review. *Agronomy for Sustainable Development*, 34(4), 707–721. <https://doi.org/10.1007/s13593-014-0245-2>
- Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science and Technology*, 43(11), 4098–4104. <https://doi.org/10.1021/es802423e>
- Phesatcha, B., Phesatcha, K., Viennaxay, B., Matra, M., Totakul, P., & Wanapat, M. (2022). Cricket Meal (*Gryllus bimaculatus*) as a Protein Supplement on In Vitro Fermentation Characteristics and Methane Mitigation. *Insects*, 13(2), 2–11. <https://doi.org/10.3390/insects13020129>
- PROTECT-ITN. (2022). Integrated RA, LCA and Energy methodology, Deliverable D5.5 <http://www.protect-itn.eu/>. <http://www.protect-itn.eu/>.
- Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE*. <https://doi.org/10.1007/978-981-15-2172-0>
- Reijs, J. W., Daatselaar, J. W. C. H. G., Helming, J. F. M., Jager, J., & Beldman, a C. G. (2013). Grazing dairy cows in North-West Europe. In LEI Wageningen UR, The Hague (Issue April 2019). https://www.wageningenur.nl/upload_mm/b/b/3/dd5ba8e2-8543-453b-904d-0189ae8341c4_Rapport_2013-001_Reijs_DEF_WEB.pdf
- Rendos, J. J., Eberhart, R. J., & Kesler, E. M. (1975). Microbial Populations of Teat Ends of Dairy Cows, and Bedding Materials. *Journal of Dairy Science*, 58(10), 1492–1500. [https://doi.org/10.3168/jds.S0022-0302\(75\)84740-0](https://doi.org/10.3168/jds.S0022-0302(75)84740-0)
- Robles, I., Kelton, D. F., Barkema, H. W., Keefe, G. P., Roy, J. P., von Keyserlingk, M. A. G., & DeVries, T. J. (2020). Bacterial concentrations in bedding and their association with dairy cow hygiene and milk quality. *Animal*, 14(5), 1052–1066. <https://doi.org/10.1017/S1751731119002787>
- Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., ... Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, 27(23), 6025–6058. <https://doi.org/10.1111/gcb.15873>
- Roibás, L., Martínez, I., Goris, A., Barreiro, R., & Hospido, A. (2016). An analysis on how switching to a more balanced and naturally improved milk would affect consumer health and the environment. *Science of the Total Environment*, 566–567, 685–697. <https://doi.org/10.1016/j.scitotenv.2016.05.141>
- Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, 16, 145–163. <https://doi.org/10.1016/j.crm.2017.02.001>
- Rong, R., & Fenech, A. (2007). Geographic Information Systems as Integrative Platforms for Climate Change Impact and Adaptation Analysis. *Linking Climate Models to Policy and*

- Decision Making, 229–237. http://projects.upei.ca/climate/files/2012/10/Book-1_Paper-10.pdf
- Rosegrant, M. W., Sulser, T. B., Mason-D’Croze, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., Zhu, T., Ringler, C., Wiebe, K. D., Robinson, S., Willenbockel, D., Xie, H., Kwon, H.-Y., Johnson, T., Thomas, T. S., Wimmer, F., Schaldach, R., Nelson, G. C., & Willaarts, B. (2017). Quantitative foresight modeling to inform the CGIAR research portfolio. April. <http://ebrary.ifpri.org/cdm/singleitem/collection/p15738coll2/id/131144>
- Rovelli, G., Ceccobelli, S., Perini, F., Demir, E., Mastrangelo, S., Conte, G., Abeni, F., Marletta, D., Ciampolini, R., Cassandro, M., Bernabucci, U., & Lasagna, E. (2020). The genetics of phenotypic plasticity in livestock in the era of climate change: a review. *Italian Journal of Animal Science*, 19(1), 997–1014. <https://doi.org/10.1080/1828051X.2020.1809540>
- Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., & Shiina, T. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering*, 90(1), 1–10. <https://doi.org/10.1016/j.jfoodeng.2008.06.016>
- Rugani, B., Maia de Souza, D., Weidema, B. P., Bare, J., Bakshi, B., Grann, B., Johnston, J. M., Pavan, A. L. R., Liu, X., Laurent, A., & Veronesi, F. (2019). Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology. *Science of the Total Environment*, 690, 1284–1298. <https://doi.org/10.1016/j.scitotenv.2019.07.023>
- Schütz, K. E., Rogers, A. R., Poulouin, Y. A., Cox, N. R., & Tucker, C. B. (2010). The amount of shade influences the behavior and physiology of dairy cattle. *Journal of Dairy Science*, 93(1), 125–133. <https://doi.org/10.3168/jds.2009-2416>
- Sharma, N., Singh, N. K., & Bhadwal, M. S. (2011). Relationship of somatic cell count and mastitis: An overview. *Asian-Australasian Journal of Animal Sciences*, 24(3), 429–438. <https://doi.org/10.5713/ajas.2011.10233>
- Shonka-Martin, B. N., Heins, B. J., & Hansen, L. B. (2019). Three-breed rotational crossbreds of Montbéliarde, Viking Red, and Holstein compared with Holstein cows for feed efficiency, income over feed cost, and residual feed intake. *Journal of Dairy Science*, 102(4), 3661–3673. <https://doi.org/10.3168/jds.2018-15682>
- St-Pierre, N. R., Cobanov, B., & Schnitkey, G. (2003). Economic losses from heat stress by US livestock industries1. *Journal of Dairy Science*, 86(SUPPL. 1), E52–E77. [https://doi.org/10.3168/jds.S0022-0302\(03\)74040-5](https://doi.org/10.3168/jds.S0022-0302(03)74040-5)
- Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., & Gerdien Prins, A. (2014). Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications.
- Steubing, B. (2015). Activity Browser. <https://activity-browser.readthedocs.io/en/latest/index.html>
- Steubing, Bernhard, de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts*, 3(December 2019), 100012. <https://doi.org/10.1016/j.simpa.2019.100012>

- Tegegne, B., & Tesfaye, S. (2017). Bacteriological milk quality: Possible hygienic factors and the role of staphylococcus aureus in raw bovine milk in and around Gondar, Ethiopia. *International Journal of Food Contamination*, 4(1), 1–9. <https://doi.org/10.1186/s40550-016-0046-2>
- Tepa-yotto, G. T., Tonnang, H. E. Z., Goergen, G., Subramanian, S., Kimathi, E., Abdelrahman, E. M., Flø, D., Thunes, K. H., Fiaboe, K. K. M., Niassy, S., Bruce, A., Mohamed, S. A., Tam, M., Ekesi, S., & Sæthre, M. (2021). Global Habitat Suitability of *Spodoptera frugiperda*. *Parasitoids Considered for Its Biological Control*, 2(1), 1–17.
- The World Bank. (2019). EIA Guidelines for Assessing the Impact of Climate Change. <https://ppp.worldbank.org/public-private-partnership/library/eia-guidelines-assessing-impact-climate-change-project>
- Tow, E. W., Letcher, A., Jaworowski, A., Zucker, I., Kum, S., Azadiaghdam, M., Blatchley, E. R., Achilli, A., Gu, H., Melike, G., & Warsinger, D. M. (2021). Modeling the energy consumption of potable water reuse schemes. *Water Research X*, 13, 100126. <https://doi.org/10.1016/j.wroa.2021.100126>
- Üçtuğ, F. G. (2019). The Environmental Life Cycle Assessment of Dairy Products. *Food Engineering Reviews*, 11(2), 104–121. <https://doi.org/10.1007/s12393-019-9187-4>
- UNEP. (2019). Making EbA an effective part of balanced adaptation strategies: Introducing the UNEP EbA briefing notes. 1, 4–7.
- UNEP. (2021). Food Waste Index Report 2021. In United Nations Environment Programme.
- UNFCCC. (2016). The Paris Agreement. <https://doi.org/10.1126/science.ns-2.26.131>
- Van Middelaar, C. E., Berentsen, P. B. M., Dijkstra, J., & De Boer, I. J. M. (2013). Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: The level of analysis matters. *Agricultural Systems*, 121, 9–22. <https://doi.org/10.1016/j.agsy.2013.05.009>
- Vida, E., & Tedesco, D. E. A. (2017). The carbon footprint of integrated milk production and renewable energy systems – A case study. *Science of the Total Environment*, 609, 1286–1294. <https://doi.org/10.1016/j.scitotenv.2017.07.271>
- Vissers, M. M. M., Driehuis, F., Te Giffel, M. C., De Jong, P., & Lankveld, J. M. G. (2006). Improving farm management by modeling the contamination of farm tank milk with butyric acid bacteria. *Journal of Dairy Science*, 89(3), 850–858. [https://doi.org/10.3168/jds.S0022-0302\(06\)72148-8](https://doi.org/10.3168/jds.S0022-0302(06)72148-8)
- Vose, D. (2000). Quantifying uncertainty about model parameters. In Wiley and Sons Ltd.. 200 (Ed.), *Risk analysis* (2 nd).
- Wald, R., Hess, C., Urbantke, V., Wittek, T., & Baumgartner, M. (2019). Characterization of staphylococcus species isolated from bovine quarter milk samples. *Animals*, 9(5), 1–16. <https://doi.org/10.3390/ani9050200>
- Wang, W., Lin, X., Jiang, T., Peng, Z., Xu, J., Yi, L., Li, F., Fanning, S., & Baloch, Z. (2018). Prevalence and characterization of *Staphylococcus aureus* cultured from raw milk taken from dairy cows with mastitis in Beijing, China. *Frontiers in Microbiology*, 9(JUN). <https://doi.org/10.3389/fmicb.2018.01123>

- Ward, P. J., Winsemius, H. C., Kuzma, S., Bierkens, M. F. P., Bouwman, A., Moel, H. DE, Loaiza, A. D., Eilander, D., Englhardt, J., Gilles, E., Gebremedhin, E., Iceland, C., Kooi, H., Ligtoet, W., Muis, S., Scussolini, P., Sutanudjaja, E. H., Beek, R. Van, Bommel, B., ... Luo, T. (2020). Aqueduct Floods Methodology. World Resources Institute, January, 1–28. www.wri.org/publication/aqueduct-floods-methodology
- WCRP. (2019). CMIP6 - Coupled Model Intercomparison Project Phase 6. World Climate Research Programme (WCRP). <https://pcmdi.llnl.gov/CMIP6/>
- Wellnitz, O., & Bruckmaier, R. M. (2012). The innate immune response of the bovine mammary gland to bacterial infection. *Veterinary Journal*, 192(2), 148–152. <https://doi.org/10.1016/j.tvjl.2011.09.013>
- WMO. (2017). Guidelines on the Calculation of Climate Normals. In WMO-No. 1203 (Issue 1203). https://library.wmo.int/doc_num.php?explnum_id=4166
- WMO. (2021). Collection of the WMO Climatological Standard Normals for 1991 to 2020.
- World Bank Group. (2021a). Climate Change Knowledge Portal For Development Practitioners and Policy Makers. <https://climateknowledgeportal.worldbank.org/>
- World Bank Group. (2021b). Metadata Climate Change Knowledge Portal (CCKP).
- World Resources Institute. (2022). Aqueduct. <https://www.wri.org/aqueduct>
- WRI. (2022). Aqueduct 3.0. World Resources Institute (WRI). <https://www.wri.org/aqueduct>
- Yan, M. J., Humphreys, J., & Holden, N. M. (2011). An evaluation of life cycle assessment of European milk production. *Journal of Environmental Management*, 92(3), 372–379. <https://doi.org/10.1016/j.jenvman.2010.10.025>
- Yang, J. bo, Wei, N., & Wen, L. fa. (2012). Month-Wise Prevalence of Subclinical Mastitis in Dairy Cows in Guangdong Province, China. *Journal of Integrative Agriculture*, 11(1), 166–169. [https://doi.org/10.1016/S1671-2927\(12\)60795-0](https://doi.org/10.1016/S1671-2927(12)60795-0)
- Yang, Y., Heijungs, R., & Brand, M. (2017). Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. 150, 237–242. <https://doi.org/10.1016/j.jclepro.2017.03.006>
- Zacarias, D. A. (2020). Global bioclimatic suitability for the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), and potential co-occurrence with major host crops under climate change scenarios. 555–566.
- Zadoks, R. N., & Fitzpatrick, J. L. (2009). Changing trends in mastitis. *Irish Veterinary Journal*, 62(4), 59–70. <https://doi.org/10.1186/2046-0481-62-S4-S59>
- Zwietering, M. H., De Wit, J. C., & Notermans, S. (1996). Application-of predictive microbiology to estimate the number of *Bacillus cereus* in pasteurised milk at the point of consumption. *International Journal of Food Microbiology*, 30(1–2), 55–70. [https://doi.org/10.1016/0168-1605\(96\)00991-9](https://doi.org/10.1016/0168-1605(96)00991-9)

LIST OF PUBLICATIONS

This thesis is based on the following publications shown below. The bibliometric information of the publications is classified by impact factor¹ and ranking according to the ISI Journal Citation Report.

JOURNAL PUBLICATIONS DERIVED FROM THE THESIS

- I. Analysing the interaction between the dairy sector and climate change from a life cycle perspective: A review**
Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
Trends in Food Science & Technology, 2022, 126, 168-179
Impact Factor = 16.002; Subject = Food science and technology; Rank Q1 2/143
<https://doi.org/10.1016/j.tifs.2021.09.001>
- II. Quantifying current and future raw milk losses due to bovine mastitis on European dairy farms under climate change scenarios**
Guzmán-Luna, P., Nag, R., Martínez, I., Mauricio-Iglesias, M., Hospido, A., Cummins, E.
Science of The Total Environment, 2022, 833, 155149
Impact Factor = 10.754; Subject = Environmental sciences; Rank Q1 26/279
<https://doi.org/10.1016/j.scitotenv.2022.155149>
- III. A toolbox to estimate variations on dairy farms' environmental impact due to climate change at different temporal and geographical horizons**
Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
Manuscript submitted to Journal of Cleaner Production
Impact Factor = 11.072; Subject = Environmental Engineering; Rank Q1 6/71
- IV. Evaluating site-specific dairy farm adaptation strategies to climate change by 2050**
Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
Manuscript to be submitted to Sustainable Production and Consumption
Impact Factor = 8.921; Subject = Green and sustainable science and technology;
Rank Q2 12/47

OTHER PUBLICATIONS

- V. Strategies to mitigate food safety risk while minimizing environmental impacts in the era of climate change**
Feliciano, R., **Guzmán-Luna, P.**, Boué, G., Mauricio-Iglesias, M., Hospido, A., Membré, J.-M.



¹ The impact factor and rank refer to 2021, which corresponds to the latest available.

Trends in Food Science & Technology, 2022, 126, 180-191
Impact Factor = 16.002; Subject = Food science and technology; Rank Q1 2/143

VI. Evaluation of food safety and environmental impacts of risk mitigation strategies by applying multi-criteria decision analysis technique: a large dairy farm as case-study

Feliciano, R., **Guzmán-Luna, P.**, Hospido, A., Membré, J.-M.

Manuscript to be submitted to Food Control

Impact Factor = 6.652; Subject = Food science; Rank Q1 9/135

VII. State-of-the art in energy use and sustainability of the dairy industry

Malliaroudaki, M.I., **Guzmán-Luna, P.**, Mauricio-Iglesias, M., Hospido, A., Bakalis, S.

Deliverable 5.1 from PROTECT-ITN (<http://www.protect-itn.eu/>), 2019

Public report

VIII. Integrated RA, LCA and Energy methodology

Guzmán-Luna, P., Feliciano, R., Malliaroudaki, M.I., Mauricio-Iglesias, M., Membré, J.-M., Gomes, R.L., Hospido, A.

Deliverable 5.5 from PROTECT-ITN (<http://www.protect-itn.eu/>), 2022

Public report

IX. Application and validation of the combined methodology

Guzmán-Luna, P., Feliciano, R., Malliaroudaki, M.I., Mauricio-Iglesias, M., Membré, J.-M., Gomes, R.L., Hospido, A.

Deliverable 5.6 from PROTECT-ITN (<http://www.protect-itn.eu/>), 2022

Public report

ORAL CONTRIBUTIONS TO CONFERENCE PROCEEDINGS

X. Modelling future scenarios within the Life Cycle Assessment framework under climate change conditions: Dairy sector as a study case

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.

FOODSIM2020 Conference, Ghent, Belgium (Online)

September 2020

XI. Modeling the effects of climate change on the environmental sustainability of the European dairy sector in the near future

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.

IV Simposio Investigación en Tecnologías Ambientales, Santiago de Compostela, Spain

September 2020



XII.

Toolbox for modelling climate change impacts on the environmental sustainability of the European dairy sector by 2050

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
13th International Conference on Life Cycle Assessment of Food 2022, Lima,
Peru
October 2022

XIII. Climate change challenges in the transition to an environmentally sustainable European dairy sector by 2050

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
36th EFFoST International Conference, Dublin, Ireland
November 2022

XIV. Modelling the effect of climate change on the current and future environmental sustainability of the European dairy sector

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
PROTECT & TRANSIT ITN symposium, Dublin, Ireland
November 2022

XV. Toolbox to model the impacts of climate change on the European dairy sector and its environmental sustainability

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
Water-Energy-Food nexus symposium (Online)
November 2022

POSTER CONTRIBUTIONS TO CONFERENCE PROCEEDINGS

XVI. Looking at improving the environmental sustainability of the dairy products value chains by the combines use of LCA and RA

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
12th International Conference on Life Cycle Assessment of Food 2020, Berlin,
Germany (Online)
October 2020

XVII. Managing climate change scenarios and its implication in the dairy sector under a life cycle perspective

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
12th International Conference on Life Cycle Assessment of Food 2020, Berlin,
Germany (Online)
October 2020

XVIII. Modelling the effect of climate change on the current and future environmental sustainability of the European dairy sector

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A.
PROTECT & TRANSIT ITN symposium, Dublin, Ireland
November 2022

JOURNAL PERMITS

These two scientific papers (see two figures below) are open access under the terms of the Creative Commons² (CC BY-NC-ND) license, which allows non-commercial use of the work as published, without adaptation or alteration. The specific contribution in each of the publications is also described.



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


Paola Guzmán-Luna: Conceptualization, Formal analysis, Data analysis, Visualization, Investigation, Writing-original draft.



Quantifying current and future raw milk losses due to bovine mastitis on European dairy farms under climate change scenarios
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CRediT authorship contribution statement

Paola Guzmán-Luna: Conceptualization, Methodology, Data curation, Data analysis, Visualization, Investigation, Writing-original draft.



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Climate change is already affecting and will continue to affect European dairy farms, the most climate-vulnerable stage in the dairy value chains. Climate hazards and their biophysical impacts are expected to modify dairy farms' environmental performance unevenly across regions and climate scenarios by 2050. The integration of tools and methodologies, such as Life Cycle Assessment, Risk Assessment, and Input-Output tables, is crucial to address this challenge. Thus, a toolbox is developed and tested in this research to provide an in-depth analysis of the biophysical impacts that climate hazards pose to the environmental performance of the sector. This research is a stepping stone in providing a scientific basis to the European dairy sector, so it can support decision-making to begin building adaptive capacity.