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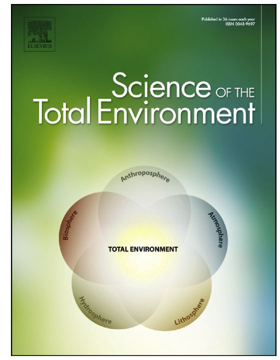

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Life cycle assessment of fish and seafood processed products – a review of methodologies and new challenges

Israel Ruiz-Salmón[a*], Jara Laso[a], María Margallo[a], Pedro Villanueva-Rey[b], Eduardo Rodríguez[b], Paula Quinteiro[c], Ana Cláudia Dias[c], Cheila Almeida[d], Maria Leonor Nunes[d,e], António Marques[d,e], Antonio Cortés[f], María Teresa Moreira[f], Gumersindo Feijoo[f], Philippe Loubet[g], Guido Sonnemann[g], Andrew P Morse[h], Ronnan Cooney[i,j], Eoghan Clifford[i,j], Leticia Regueiro[k], Diego Méndez[k], Clémentine Anglada[l], Christelle Noirot[l], Neil Rowan[m], Ian Vázquez-Rowe[n], Rubén Aldaco [a].

[a] Departamento de Ingenierías Química y Biomolecular, Universidad de Cantabria, Avda. de Los Castros, s.n., 39005 Santander, Spain

[b]EnergyLab, Fonte das Abelleiras s/n, Campus Universidad de Vigo, 36310 Vigo, Galicia, Spain

[c]Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[d]IPMA - Instituto Português do Mar e da Atmosfera (IPMA), Divisão de Aquacultura, Valorização e Bioprospeção, Avenida Doutor Alfredo Magalhães Ramalho 6, 1495-165 Lisboa, Portugal

[e]CIIMAR - Centro Interdisciplinar de Investigação Marinha e Ambiental, Terminal de Cruzeiros do Porto de Leixões, Avenida General Norton de Matos, S/N, 4450-208 Matosinhos, Portugal

[f]Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Galicia, Spain

[g]Univ. Bordeaux, CNRS, Bordeaux INP, ISM, UMR 5255, F-33400, Talence, France

[h]School of Environmental Sciences, University of Liverpool, Liverpool, U.K.

[i]College of Engineering and Science, National University of Ireland, Galway H91 HX31, Ireland. Ryan Institute, NUI Galway, Ireland.

[j]Ryan Institute, NUI Galway, Ireland

[k]ANFACO-CECOPESCA, Campus University 16, 36310 Vigo PO, Spain

[l] Research consultant, VertigoLab, Darwin Ecosystème, 87 Quai de Queyries, 33100 Bordeaux, France

[m] Bioscience Research Institute, Athlone Institute of Technology, Ireland

[n]Peruvian LCA Network (PELCAN), Department of Engineering, Pontificia Universidad Católica del Perú, Avenida Universitaria 1801, San Miguel, 15088 Lima, Peru

*Corresponding author: Tel: +34 942 200931

E-mail address: Israel.ruizsalmon@unican.es

ABSTRACT

Life cycle assessment (LCA) has been widely applied in many different sectors, but the marine products and seafood segment have received relatively little attention in the past. In recent decades, global fish production experienced sustained growth and peaked at about 179 million tonnes in 2018. Consequently, increased interest in the environmental implications of fishery products along the supply chain, namely from capture to end of life, was recently experienced by society, industry and policy-makers.

This timely review aims to describe the current framework of LCA and it's application to the seafood sector that mainly focused on fish extraction and processing, but it also encompassed the remaining stages. An excess of 60 studies conducted over the last decade, along with some additional publications, were comprehensively reviewed; these focused on the main LCA methodological choices, including but not limited to, functional unit, system boundaries allocation methods and environmental indicators.

The review identifies key recommendations on the progression of LCA for this increasingly important sustaining seafood sector. Specifically, these recommendations include (i) the need for specific indicators for fish-related activities, (ii) the target species and their geographical origin, (iii) knowledge and technology transfer and, (iv) the application and implementation of key recommendations from LCA research that will improve the accuracy of LCA models in this sector. Furthermore, the review comprises a section addressing previous and current challenges of the seafood sector. Wastewater treatment, ghost fishing or climate change, are also the objects of discussion together with advocating support for the water-energy-food nexus as a valuable tool to minimize environmental negativities and to frame successful synergies.

KEYWORDS

Life cycle assessment, seafood, fisheries, nexus, environmental impacts, sustainability

1. INTRODUCTION

The 17 Sustainable Development Goals (SDG), launched by the United Nations (UN) for the 2030 agenda, seek "*a shared blueprint for peace and prosperity for people and* *the planet, now and into the future*" (Sustainable Development Goals, 2020). Among these, SDG-14, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", specifically addresses the priceless environmental, cultural and social wealth of these water bodies that produce half of the oxygen we breath and provide 16% of the animal protein we eat (European Commission, 2019a). Therefore, addressing these goals are essential for human survival, not only from a biological, but also from a sustaining socio-economic perspective. More specifically, goal SDG-14 focuses on the widely known 'blue economy'; that is, all activities related to oceans, seas and littoral environments including marine living resources, marine extraction of non-living resources, maritime transport, port activities, shipbuilding and repair, and coastal tourism.

In 2018, the production of global capture fisheries reached the highest level ever recorded at 96.4 million tonnes (live weight); whereas, the aquaculture sector attained another all-time record high of 82.1 million tonnes. The labour force involved in the primary sector for fisheries and aquaculture is represented by a total of 59.5 million people (FAO, 2020). China leads the sector as attested to accounting for 35% of the global fish production that is followed by other Asian countries (34%), America (14%), Europe (10%), Africa (7%) and Oceania (1%). In general terms, total fish production followed an increasing trend but was geographically differenced: Asia and Africa have almost doubled their production in the past two decades and America fluctuated since the peak of the mid-1990s due to the strong influence of El Niño – Southern Oscillation on the abundance of anchoveta (*Engraulis ringens*). Whereas Europe suffered a gradual decline since the late 1980s that was buffered in recent years (FAO, 2020).

Beyond the macro data, the sustainability of the seafood sector involves maintaining a complex and dynamic equilibrium: namely, to: i) guarantee social protection for fishermen and fish farmers (Maritime Labour Convention, 2006) and subsidisation (Sumaila et al., 2019); ensure the periodical renewal of fishing grounds and the biodiversity preservation (Johnson et al., 2019), iii) keep the quality and security ruled by the standards of the food supply chain (Gephart et al., 2017); and, iv) face climate change consequences (Peck and Pinnegar, 2018) and other environmental negativities related to captures (e.g., ghost fishing, fuel leaks) or processing stages (e.g., waste streams). To deal with these complex issues, significant efforts have been made to establish an appropriate legal framework at different levels, particularly the need to progressively apply an environmental approach across many different sectors. Notably, the inclusion of environmental public criteria in decision-making is of paramount relevance, which address the provision of important information about the use of resources from raw materials to water and energy. Although the Blue Economy only represents 2.2% of employment in the European Union (EU)-28 along with a gross domestic product estimated at €15900 billion (€13500 without the UK) in 2018 (European Commission, 2020a), the continent has a long history of applying high standards related to environment, food production and consumption policies. The European Commission implemented a shared-management perspective of the oceans and seas through the Common Fisheries Policy (CFP) (European Commission, 2020b) in the 1970s and, more recently, a Green Deal to combat climate change and decouple economic growth from resource use. The implementation of the Circular Economy Action Plan reported in 2019 (European Commission, 2019b), the obligation of landing all discards in 2020 (European Commission, 2018a) or the ban of single-use plastics to minimize marine litter starting in 2021 (European Commission, 2018b) are some of the latest policy strategies in this regard (Ruiz-Salmón et al., 2020). In addition, EU members are also forced to promote policies under this framework and some of them are in place. For instance, Spain, with a coastline of almost 8,000 km and the largest fishing industry in the EU, recently designated the agri-food and seafood sector as a priority intervention in the Spanish Circular Economy Strategy (SCES) (Spanish Government, 2020).

A quarter of global greenhouse gas emissions related to food production (Poore and Nemececk, 2018). Consequently, a grand challenge is to effectively promote the production of high-quality food at it' origin that have affordable prices along with commensurately reducing the impact derived from its production, both in terms of emissions, water use, non-valued waste. Also, emphasis should be placed on reducing the impact derived from the generation of waste both in the field of production and arising from consumption. Notably, the SCES strongly recommends an increase in energy efficiency and a reduction of carbon dioxide (CO_2) emissions from the seafood sector: thus, promoting efficient control of fisheries and data collection through improving knowledge in decision-making that underpin adaptation of products to consumer demand, reduce waste or improve recycling will add significant value. These recommendations will be enabled and advanced through applying life cycle assessment (LCA). LCA is the most established scientific tool for environmental analyses as it can fully address the quantification of footprints (e.g., energy, water, carbon) and environmental impact categories (e.g., global warming, eutrophication, human toxicity, etc.) along the life cycle of products and processes by studying the inputs (e.g., resources) and outputs (e.g., residues, by-products) of the system (ISO, 2006a, 2006b). Briefly, an LCA follows 4 inter-related stages: 1) statement of the goal and scope of the study, including the limits of the system and the functional unit; 2) development of inventory flows (inputs and outputs); 3) evaluation of the potential environmental impacts; and, 4) interpretation of the results drawing conclusions and recommendations.

Although LCA has been applied for decades, initially it focused on packaging, energy use and emission reductions in the 1960s. Following a gap in 1970s that coincided with methodological development, the first standardization occurred before the end of the millennium. Notable developments in the early 2000s included the release of the first datasets that emphasised increasing interest in the use of LCA as a potentially disruptive tool applied to national energy systems and waste management systems, among others. In the last two decades, LCA has experienced a methodological consolidation and a commensurate international collaboration across many sectors, such as business, research and innovation, product or process design, education, policy development, labelling, food and agriculture, consumer goods and energy industries (Hauschild et al., 2018). Nowadays, LCA is already part of the Single Market for Green Products Initiative launched by the European Commission (European Commission, 2013). Moreover, Product Environmental Footprint Category Rules (PEFCRs) are currently being updated with marine fish, including both fisheries and aquaculture production of live, fresh, chilled and frozen fish, as well as manufactured products, processed and preserved fish, crustaceans and molluscs (EC, 2020c). LCA has also been highlighted as an important tool to help companies pivot beyond COVID-19, including transitioning for uptake of new green deal innovations and services (Rowan and Galanakis, 2020).

In parallel, scientific LCA publication linked to the capture, farming and processing of fish started in mid-2000 where the LCA-related publications strongly increased from less than 20 cited in 2010 to more than 90 in 2019. Avadí and Fréon (2013) published one of the first reviews on LCA as applied to fisheries that was based on 16 studies issued in the first decade of 2000: these included the typical LCA phases: goal and scope definition, inventory analysis, impact assessment and interpretation. Other LCA reviews published by Vázquez-Rowe et al. (2012) and Ziegler et al. (2016) also delved primarily into the fisheries sector and associated supply chain, whereas other groups focused on the aquaculture sector (Henriksson et al., 2012; Bohnes et al., 2019). More recently, Avadí et al. (2020) published another LCA review where the main objective was to present the first effort to aggregate and standardize seafood-related datasets in the Ecoinvent database. This LCA also explained the main data sources and commensurate methodological choices used in the building of the datasets. In this context, the current LCA review advances this topic by addressing the whole supply chain of the seafood sector with a particular focus on the fisheries sector. More specifically, the aim of the review is to assemble LCA-based studies published in the past decade, to analyse the evolution in research and innovation, and to describe the database and assessment models. Moreover, hotspots, challenges and opportunities arising from the current seafood sector are discussed from different perspectives including as climate change, economic market and environmental protection as well as the nexus between food, energy and water. No prior published literature review focused on this LCA-nexus integration has been reported. Overall, given the nature of bibliometric analysis performed, the expected audience of this review study are LCA practitioners. However, given the description of the utility and scientific challenges, this review will also appeal to broad range of stakeholders in the seafood sector, especially fish managers in the public and private sectors, and NGOs which will help future proof the sector.

2. MATERIALS AND METHODS

The importance of the eco-perspective has been introduced in an increasing number of frameworks due to the historic push of the environmental movements and the multiple responses given by the rest of the actors. Occasionally, it is reflected in an eco-friendly commitment from policy-makers, companies and citizens. There are also instances of an eco-style approach to informing communities or green-washing campaigns from industries and big corporations. Nowadays, environmental awareness is a prominent cross-cutting key topic that features strongly in an increasing number of scientific publications along with permeating and influencing adjacent disciplines. In this context, this review addresses LCA studies applied to the fishing sector that focuses mainly on wild fish capture fisheries. It also commensurately addresses seafood processing and other stages of its life cycle based on their inclusion as topics appearing in system boundaries in publihed literature reviewed.

The bibliometric analysis was conducted using Scopus, which is the largest abstract and citation database of peer-reviewed literature; it addressed over 20,000 journals (Geng et al., 2017). This approach provides several options to make the search more accurate and reliable including use of keywords. Thus, three kinds of searches were applied using Scopus as a first step to appraise the breadth of LCA application in marine products and processes during the period 2010 to 2019: 1) using the search term “life cycle assessment” and combining this with 2) “food” and 3) “fish” and “seafood”. A total of 537 files were found in the literature search for the period analysed. Figure 1 highlights an increasing use of LCA studies over the last decade where it appeared in almost 100 publications in both 2018 and 2019. Notwithstanding same, the seafood sector still represents a very low percentage of LCA-published studies that focused on food. Although the search included all kinds of publications, i.e., articles, reviews, conference papers, books, reports, etc., most of them (67-70%) were articles and about 76-83% involved articles or reviews. Thus, a refinement in the literature search was made combining “life cycle assessment” and “fish” or “seafood” terms only on titles, abstracts and keywords. The scope was reduced to 243 documents (198 English full-length articles). Finally, other papers were excluded because the subject area was out of scope -health, mathematics or engineering- (73) or addressed LCA related to diets (15), packaging and food waste (7), only aquaculture species (7), or did not include a case study.

In brief, 69 LCA-related publications have been extensively analysed for this review. Figure 2 shows the 20 scientific journals where these articles were published. Two of these, the International Journal of Life Cycle Assessment and the Journal of Cleaner Production, represented 43% of the LCA publications that were included in this work. From all the publications assessed, 59 were case studies that included LCA impact categories along with occasional fisheries management indicator work. The other 10 studies encompassed two studies of Avadí and co-authors; namely, a general disposition to LCA (Avadí and Fréon, 2013), and a partial life cycle inventory review (Avadí et al., 2019). Other publications related to the best available techniques (BATs) in the fishing sector (Barros et al., 2009; Bello Bugallo et al., 2013), ecolabeling and certification (Thrane et al., 2009b; Vázquez-Rowe et al. 2016), best practices in LCA implementation and guidelines for managers and policy-makers (Vázquez-Rowe et al., 2012b; Vázquez-Rowe and Benetto, 2014), or regional context of fisheries in Peru (Fréon et al., 2014a) and seafood processing in Denmark (Thrane et al., 2009a). Among the 59 case studies, almost 90% were published after 2010 with only 7 appearing before that year; thus, making this present review representative of the previous decade.

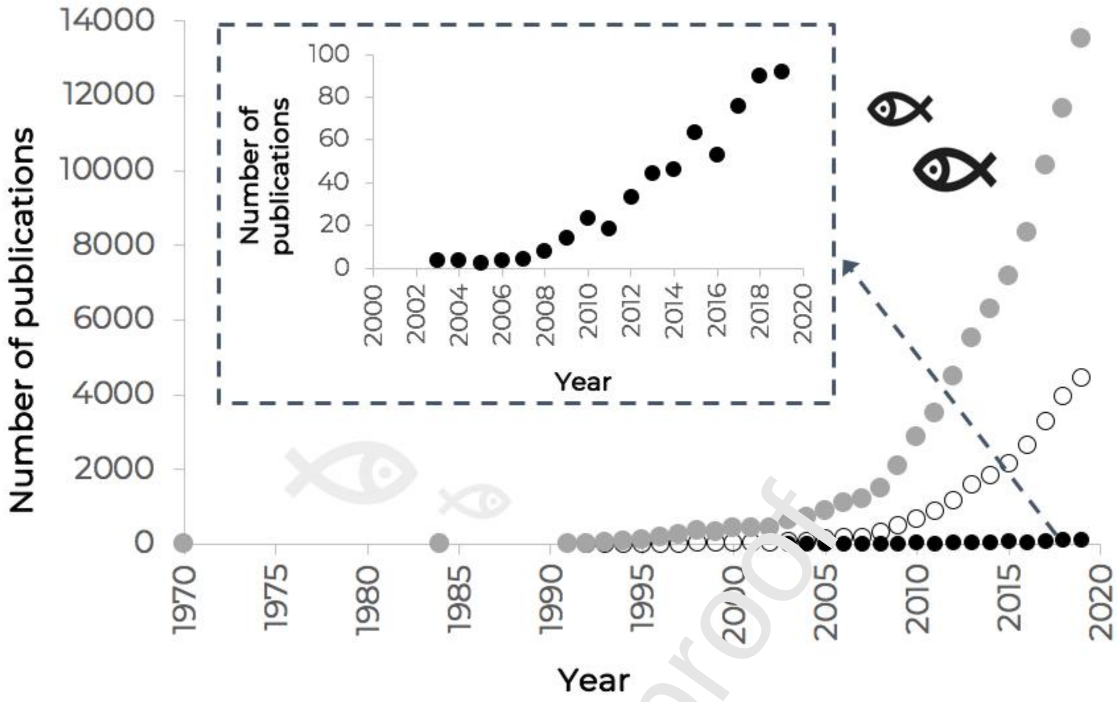

Figure 1. Number of publications per year in scientific journals that include the search terms "life cycle assessment" (circles), plus "food" (cross) or plus "fish" and "seafood" (diamond) accessed in Scopus in June 2020.

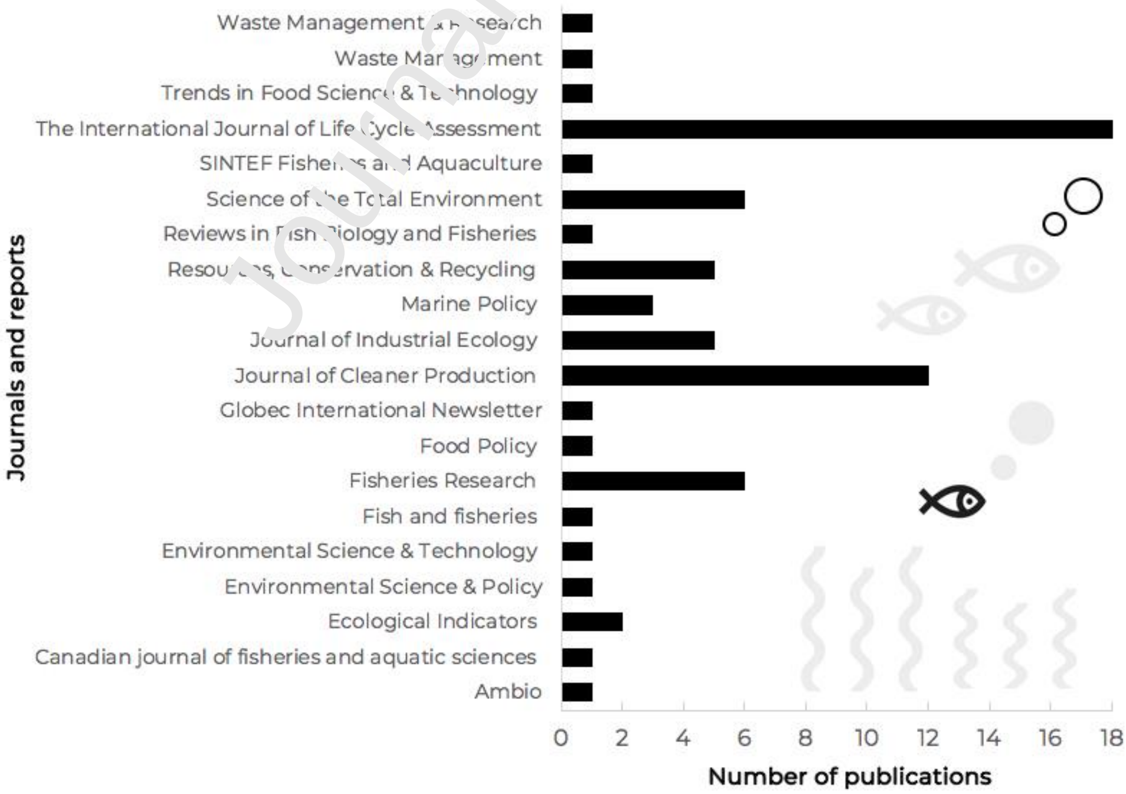

Figure 2. Distribution of the 69 publications analysed according to the journal of publication.

This review does not include aquaculture despite its products representing approximately 15% of the worldwide fish production between 1986 -1995: where the present day level of production is approximately 46% (FAO, 2020). Advances in science and technology have mirrored economic and labour growth in terms of rate of growth. A number of studies have comprehensively reviewed state-of–the-art in LCA for enhancing aquaculture over the past two years (Bohnes et al., 2018; Bohnes and Laurent, 2019; Philis et al., 2019). However, aquaculture was not a major focus of the current study, as mentioned in section 1, although this particular sector is partially addressed in the discussion. Studies linked to the production of mussels in mussel rafts, along the coast of Galicia (Spain), were included within the scope of the current review given the fact that an auxiliary fishing fleet is needed to attend the production of this oceanic infrastructure.

The review follows the structure of the ISO standards 14040 and 14044 on LCA (ISO, 2006a, 2006b), also suggested by Avadí and Fréon (2013), yet advances this area much further by way of addressing new concepts linked to LCA in cross-cutting fields of study along with embracing current challenges facing the fishing sector. Firstly, a discussion focusing on the main LCA principles and requirements is addressed through use of several tables linked to text in which case studies were desegregated for ease of comparison: these included goal and scope, boundaries of the system, functional unit and life cycle impact assessment methods, impact categories and so forth. Thereafter, this constitutes the first study that comprehensively reviews use of LCA research for addressing the development of the fishing sector from a global perspective. Finally, the relationship or nexus between energy, water and food is discussed in addition to articulating previous and ongoing implications that hinder technical and environmental progress across the sector, such as marine debris, ghost shipping and climate change.

3. RESULTS AND DISCUSSION

3.1. Goal and scope definition

The goal definition is framed on addressing key questions, such as, "why do we perform an LCA?", "who are the target audiences?" and "what is the product under study?" However, the scope definition is more complicated as it includes the definition of the system boundaries, the functional unit, the allocation strategy and other relevant hypotheses and assumptions (ISO, 2006a. 2006b). Table 1 presents some of the main characteristics of the reviewed LCA studies: namely, targeted species, functional unit, system boundaries, allocation method and sensitivity analysis.

3.1.1. Functional unit definition

The functional unit (FU) is the element that quantifies the function of the system, the calculation basis for which all inputs and outputs of the system must refer. The selection of a coherent FU is a fundamental step in order to perform a robust and comparable LCA. Choosing an appropriate FU allows direct comparison between alternative scenarios that perform the same function. However, FUs vary greatly, which highlight the difficulties of comparing results reported across many different articles. In this study, the choice of different FUs in the reviewed studies was assessed in detail. Around 30% of analysed papers focused their research on the extraction phase and use the amount of product landed in a port as the FU, typically 1 kg or 1 tonne. For instance, Abdou et al. (2018) defined their FU as 1 tonne of landed seafood (shrimp, demersal finfish, mullets, rays and sharks) by demersal trawlers in the Gulf of Gabes. Avadí et al. (2015) used 1 ton of landed fish by the Peruvian anchoveta purse seining fleet in the period 2005-2010 as the study FU. This FU was also used by Lourguioui et al. (2017) to assess mussel cultivation, Avadí et al. (2018) to address Peruvian hake capture, Fréon et al. (2014b) to analyse the Peruvian anchoveta caught in the north-centre fishing zone of Peru and González-García et al. (2015) and Villanueva-Rey et al. (2018) to assess European pilchard capture. However, in some cases, such as Driscoll et al. (2015), this perspective includes other life cycle stages in the FU, such as transportation to the processing plant.

An alternative FU was used when studies focused on the processing stage. For example, Barros et al. (2009) analysed the operation of a mussel processing plant for one year, while Bello-Bugallo et al. (2013) sought to characterise the operation of different seafood processing plants by the degree of implementation of BATs and an output-based FU was used. A similar case was analysed in Denham et al. (2016), where 1 tonne of processed fish sold at retail was used as the FU. Mass of packaged product ready for dispatch was a FU used by several authors. Findings of Ziegler et al. (2011), which was replicated in 2012 and 2016 but not included in the tables, defined the FU as 1 kg of shrimp and the accompanying packaging material ready to import to Europe. Almeida et al. (2015) used 1 kg of edible product (i.e., canned sardine with olive oil) as FU, whereas Avadí et al. (2014b) used 1 kg of fish (Peruvian anchoveta) in the final product. Other authors defined the FU as the commercial or serving fish product (Ziegler et al., 2003; Ziegler and Valentinsson, 2008). For example, Iribarren et al. (2010d) used one triple pack of round cans of canned mussels composed by 129 g of canned mussel flesh, 120 g of sauce, 81 g of tinplate can and 12.73 g of cardboard as the FU. Similarly, Laso et al. (2017a) selected one “octavillo” (i.e., a special can with the right amount of product, usually served as individual ration) of canned anchovy as the FU, which was composed by 30 g of canned anchovy, 20 g of extra virgin oil, one aluminium can and cardboard. Parker and Tyedmers (2012a) defined three FUs in accordance with the three Antarctic krill-derived products studied: 1 kg of krill meal, 1 L of krill oil and 1 consumer-ready bottle of 60 omega-3 krill oil capsules. On the other hand, Svanes et al. (2011) defined a specific FU for each of the four-derived cod products under study – wetpack, burger, loin and processing residues to animal feed. Vazquez-Rowe and co-workers (2011a, 2013a) analysed two types of hake: production of 500 g of raw gutted fresh hake fillet reaching the household including packaging and 1 package of frozen fish sticks containing 10 fish sticks, which corresponds to approximately 320 g of edible product. Based on a nutritional point of view, some authors defined the FU as the amount of protein supplied to consumer. For instance, Vázquez-Rowe et al. (2014b) used the amount of protein (17.26 g) supplied by one can of sardines (85 g) in olive oil produced by a Galician canning industry as the FU, whereas Fréon et al. (2010) defined the FU as 100 g of animal protein of anchoveta or derivative product on the consumer plate.

However, another trend has been to analyze a feedstock-based FU. Hospido et al. (2006) analysed the production of canned tuna and the FU evaluated was 1 tonne of raw tuna entering the factory. Similarly, Laso et al. (2017b) assessed the production of canned anchovy and the selected FU was also 1 kg of raw anchovy entering the factory. Both options present different advantages that are worth emphasizing. Choosing an input-based FU allows for comparison of the environmental performance of different processes, which simultaneously determines the strengths and weaknesses of these processes. In contrast, selecting an output-based FU allows for detailed product analysis, including its use as a key step in eco-labelling. Fréon et al. (2017) evaluated two scenarios: firstly, the production of fishmeal and fish-oil as by-products of fishing for which an output-based FU (one tonne of by-product produced) was used. However, Laso et al. (2016) evaluated the valorisation of anchovy residues by means of the production of fishmeal and fish oil defining an input-based FU (1 tonne of anchovy residues). Similarly, Iribarren et al. (2010b) addressed the valorisation of mussel shells and mussel organic remains using an input-based FU (100 tonnes of each residue). Alternatively and secondly, Fréon et al. (2017) aimed at analysing the intrinsic characteristics of the processing process, for which a feedstock-based FU was chosen (1 ton of raw material). Even though they do not follow a conventional LCA approach, the studies by Hallstrom et al. (2019) and Hélias et al. (2018) are also noteworthy. Hallstrom et al. (2019) sought to establish a nexus between the carbon footprint and the nutritional impact of Swedish seafood consumption, for which the author makes a relative comparison between the results and their variation from the median value. Hélias et al. (2019) used fishery operations to develop characterization factors that allow determining biotic resource depletion.

3.1.2. System boundaries

The reasons that influence an author to decide which processes should be included within the boundaries of the system must be duly justified, including what are the clearly defined criteria that govern this decision, and justify same. Studies included in this LCA review show some variability in the definition of the system boundaries. Thus, the scope of the analysis will depend on the approach of the system (Figure 3): "cradle to grave", involving all stages of the life cycle; "cradle to gate" or "gate to grave", including limits from the beginning of the cycle to a specific "gate" (e.g., from capture to landing, from capture to get the product, etc.) or from a midpoint to the end of life stage, respectively; "gate to gate", for intermediate stages; or specific parts of the life cycle, such as the end of life, product components, etc. (ISO, 2006a, 2006b). Regarding fishery-related LCA studies, system boundaries usually include at least the use and maintenance of the vessel (Almeida et at., 2014; Driscoll and Tyedmers, 2010), while in other cases construction (Abdou et al., 2018; Avadí et al., 2014b; Avadí et al., 2018; Driscoll et al., 2015; González-García et al., 2015; Hospido and Tyedmers, 2005, Ramos et al., 2011; Vázquez-Rowe et al., 2010a, Vázquez-Rowe et al., 2010b; Vázquez-Rowe et al., 2011b) and end of life stages (Fréon et al., 2014b; Laso et al., 2018b) are also included. Only two studies assessed the consumption of fuel within the fishing activity (Parker et al., 2014; Thrane, 2004), distinguishing between fuel used during propulsion to reach fishing grounds and fuel used during the actual extraction of fish. Alternatively, Lozano et al. (2010) considered mussel cultivation farming, including the construction, operation and maintenance of mussel rafts. However, these authors also addressed the environmental impact of the auxiliary boats used by the sector to reach the rafts, which are usually located several miles away from the coast. Beyond vessel and farming-related activities, the systems commonly end at the harbour, when fish is landed. Within the sample analysed, a small number of studies included fish transport to the processing plant -e.g. Farmery et al. (2015), while others included transport to retail (Driscoll et al., 2015).

With regard to studies focusing on processing, the most recurrent feature is that the system boundaries include activities carried out directly in the processing plant, in addition to ancillary operations such as power or steam production, excluding the fishing or farming stage (Iribarren et al., 2010a). On the other hand, some authors considered the fishing stage together with processing (e.g. Almeida et al., 2015; Avadí et al., 2018). Fréon et al. (2017) also included the fishing stage within the boundaries of fishmeal and fish-oil production, which allowed performing an exhaustive study of the environmental impacts related to the production of these co-products. Svanes et al. (2011) and Vázquez-Rowe et al. (2012a) added one additional step along with including the distribution to retailer of cod and octopus' products, respectively. Winther et al. (2009) and Ziegler et al. (2012) also included the transportation of Norwegian seafood products to the wholesaler. Other authors advanced thee activities further; for instance, Hospido et al. (2006) also analysed transportation stages to wholesale and consumption at the households that followed a gate-to-grave approach. Similarly, Fréon et al. (2010) and Laso et al. (2017a) assessed the whole life cycle of Peruvian and European anchovy, respectively, considering anchovy capture, production, transport, use and disposal. Vázquez-Rowe et al. (2011a) analysed the life cycle of fresh hake including the household consumption. Denham et al. (2016) included the transportation of all consumable items to city and regional retailer and waste disposal to landfill. In summary, the majority of studies were cradle-to-grave analysis, with some studies adopting either gate-to-gate or gate-to-cradle type approaches.

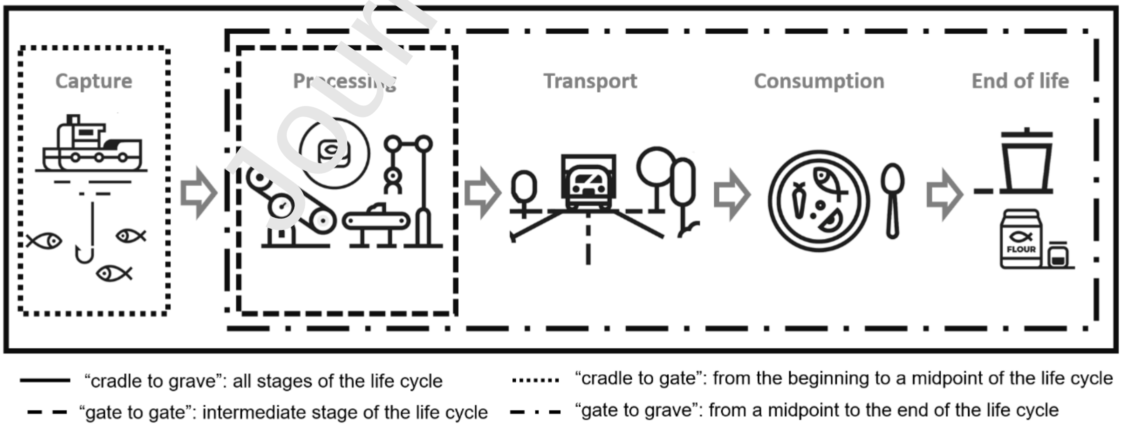

Figure 3. System boundaries applied in LCA for the seafood sector.

3.1.3 Allocations

Multifunctional processes are those economic systems that i) produce more than one valuable output (multi-output) (Huijungs and Guinée, 2007), ii) have more than one input (multi-input), such as waste treatment processes with a mixture of input waste flows (Iribarren et al., 2010c); or iii) transform a product into another product (open-loop recycling). In all these systems, the environmental burdens associated with a particular process must be partitioned over the various functional flows of that process (Margallo et al., 2014).

To handle this multifunctional problem, the ISO standard (ISO, 2006a, 2006b) establishes a preference order that consists on dividing processes into sub-processes, or expanding system boundaries to include the additional functions. If that is not possible, then the allocation problem must be solved by using physical causation or other relationships, including the economic value, mass or energy content of the functional outputs (Azapagic and Clift, 1999). In other circumstances, allocations are not needed as authors focus on the contribution of each production stage or fishing gear to the environmental impacts, instead of the impact associated to the different species landed (Abdou et al., 2018; Lozano et al., 2010).

Most of the LCA studies analysed in this review can be classified as multi-output process. The most common need for allocation arises when fishing fleets land by-catch (organisms inadvertently captured while fishing for more valuable or legally permitted species) or target multiple species. In these cases, the use of system expansion is not usually implemented due to the lack of fisheries where only the by-catch species are caught (Ayer et al., 2007). Exceptionally, Thrane (2004, 2006) applied a combination of technical subdivision along with system expansion, mass and economic allocation to conduct an energy analysis and an LCA, respectively. In mass and economic allocation, the fuel consumption and impacts were distributed to each species based on the proportion to their weight and the catch value. Ideally, the system expansion should consider that a by-catch of a particular species affects the fishing vessels targeting that species, as their quotas are reduced proportionally to meet the overall quota -in those countries that fix it- (Thrane, 2004). Hence, the by-catch substitutes catch (or quota) in other Danish fisheries, which targets these species (Thrane, 2006).

Nonetheless, in most studies, multi-output fishery systems are solved using mass, energy or economic allocations. Despite that, some authors define mass allocation as arbitrary and unjustified; however, this procedure has been widely applied (e.g. Avadí et al., 2015; Avadí and Fréon, 2015; Avadí et al., 2018; Driscoll et al., 2015; Parker et al. 2014; Vázquez-Rowe et al., 2014b; Vázquez-Rowe et al., 2016; Villanueva-Rey et al., 2018; Winther et al., 2009) because there is no other way to particularize inputs to specific species during fishing operations. On the other hand, economic allocation has generally been defended as a reasonable and more socially relevant approach (Ayer et al., 2007). However, several authors point out that the main problem of this approach is the highly volatile economic price of the product, which depends on the season, freshness of the product and many other market factors (Vázquez-Rowe et al., 2013a; Vázquez-Rowe et al., 2011a), making it difficult to establish a stable allocation over time (Winther et al., 2009). Pelletier and Tyedmers (2011) warn about the difficulties of applying economic criteria to partition natural systems.

Contrasting several allocation methods provides more robust and precise LCA results Avadí and Fréon 2013). This type of approach, using economic and mass allocation was conducted in several studies (Fréon et al., 2019; Vázquez-Rowe et al., 2011a). Vázquez-Rowe et al. (2011a) compared the use of mass and economic allocation for fresh hake fillet captured by the Galician, founding similar results since the average sale price for European hake does not entail major differences. However, the use of economic allocation was shown to be preferred to mass allocation in mixed fisheries where the landed species have great differences in economic value (Ayer et al., 2007). Ramos et al. (2011) proposed a temporal allocation for the evaluation of fishing of North East Atlantic Mackerel (NEAM). This procedure was applied to construction and maintenance materials, as the Basque coastal purse-seining fishing fleet presents three distinct fishing seasons. Fishing activity is focused on NEAM and on the anchovy during the first half of the year, while the albacore fishing season takes place in the second half of the year.

In the case of fish processing, the main allocation problem is obtaining data of secondary co-products. In these studies, the use of system expansion is more common, since it is easier to find an alternative by-product. Additionally, the substitution by another fishery or non-fishery protein source is always possible (Avadí and Fréon 2013). The valorisation of shells and mussel meat by-product was allocated by substitution to alternative products. Mussel shells can be used as raw material for calcium carbonate production and it was assumed that 100 t of shells avoids the conventional production of 65 t of calcium carbonate (Iribarren et al., 2010b). Similarly, the valorisation of organic waste from anchovy canning plants results in anchovy paste (from remaining anchovies) and fishmeal and fish oil (from head and spines). The impact of these co-products was allocated using a system expansion based on substitution for alternative products (Laso et al., 2016, Laso et al., 2017a, Laso et al., 2017b, Laso et al., 2018a, Laso et al., 2018b, Laso et al., 2018c). Particularly, these authors assumed that 1 t of anchovy paste substituted the production of 1 t of tuna pâté given its similar protein content, whereas 1 t of heads and spines replaced the production of 212 kg of fishmeal and 108 kg of fish oil from fresh anchovy (Laso et al., 2016). This assumption was compared with mass and economic allocation (Laso et al., 2017b). Similarly to fisheries, if there is a lack of alternative production systems for the by-product under analysis, causality or non-causality allocation were applied (Vazquez-Rowe et al., 2013a; Winther et al., 2009).

Table 1. Main characteristics of the reviewed LCA studies: Functional Unit, System Boundaries, Allocations and Sensitivity analysis.

Reference	Targeted species	Functional unit	System boundaries	Allocation method	Sensitivity analysis
Abdou et al., 2018	Shrimp and demersal finfish (*Sparidae Diplodus annularis, Sparus aurata*), mullets (*Mullus barbatus, M. surmuletus*), rays (e.g. *Raja clavata*) and sharks (e.g. *Mustelus mustelus*).	1 t of landed seafood	Cradle to gate	No	No
Abdou et al., 2020	Shrimp and demersal finfish (*SparidaeDiplodus annularis, Sparus aurata*), mullets (*Mullus barbatus, M. surmuletus*), rays (e.g. *Raja clavata*) and sharks (e.g. *Mustelus mustelus*).	1 t of landed seafood	Cradle to gate	No	Yes, management scenarios: establishment of marine protected areas, extension of the biological rest period, and decrease in the number of demersal trawlers.
Almeida et al., 2014	European pilchard (*Sardina pilchardus*)	1 kg of landed sardine,	Cradle to gate	Mass	Yes, gear and time lapse comparison.
Almeida et al., 2015	European pilchard (*Sardina pilchardus*)	1 kg edible of canned sardine with olive oil	Cradle to gate	Mass	Yes, packaging analysis and comparison with other seafood products.
Avadí et al., 2014a	Peruvian anchoveta *(Engraulis ringens)*	1 kg of fish in the final product	Cradle to gate	Mass	Yes, electricity reduction, packaging material and reduction in-plant discards.
Avadí et al., 2014b	Peruvian anchoveta *(Engraulis ringens)*	1 t of landed fish	Cradle to gate	No	Yes, Data Envelopment Analysis (DEA) to determine the relative efficiencies of multiple comparable units.
Avadí et al., 2015	Ecuadorian tuna yellowfin *(Thunnus albacares)*, skipjack *(Katsuwonus pelamis)* and bigeye *(Thunnus obesus)*	1 t of tuna product	Cradle to gate	Mass	Yes, fuel use intensity and packaging material.
Avadí and Fréon, 2015	Peruvian anchoveta *(Engraulis ringens)*, trout *(Oncorhynchus mykiss)*, tilapia *(Oreochromis spp.)* and black pacu *(Colossoma macropomum)*	1 t of edible fish in a Direct Human Consumption product in the case of	Cradle to gate	Mass	No

		anchoveta and fresh fish edible portion for cultured species.			
Avadí et al., 2018	Peruvian hake (*Merluccius gayi peruanus*)	1 t of whole hake landed	Cradle to gate	Mass	Yes, fuel use intensity and comparison with published results from other hake fisheries and with another Merlucciidae fish, the Patagonian grenadier (*Macruronus magellanicus*).
Avadí et al., 2019	South Pacific anchovies and hake (including *Patagonian grenadier-Macruronus magellanicus*) and Pacific tunas (*Thunnus spp.*), tilapia (*Oreochromis spp.*) and trout (*Oncorhynchus mykiss*)	N/A	Cradle to grave	Mass, economic	No
Denham et al., 2016	Different species of finfish: Crimson snapper (*Lutjanus erythropterus*), Bluespotted emperor (*Lethrinus punctulatus*) and Rosy threadfin bream (*Nemipterus furcosus*) among others.	1 t of processed fish sold at retail	Gate to gate	Mass	Yes, cleaner production strategies: solar electricity, biogas electricity, reduction of GHG emissions from refrigeration, and utilizing waste to develop by-products.
Driscoll and Tyedmers, 2010	Atlantic herring (*Clupea harengus*)	1 t of fish landed	Cradle to gate	N/A	Yes, variations of Total Allowable Catch and purse seine fishing effort.
Driscoll et al., 2015	American lobster (*Homarus americanus*)	1 t of live lobster	Cradle to gate	Mass	Yes, comparison of different scenarios: no allocation between the main product and co-products, electricity use for storage, fuel use in vessel, different database for fuel combustion and post-capture mortality rate.
Farmery et al., 2015	White banana prawn (*Fenneropenaeus merguiensis*)	1 kg of frozen prawn	Cradle to gate	Mass	Yes, comparison of impact method (IPCC 100 years,

					CML 2 Baseline 2000 and ReCiPe). Also catch variation: 10% increase and decrease in catch with the same number of boat days.
Fréon et al., 2010	Peruvian anchoveta (*Engraulis ringens*)	100 g of protein	Cradle to gate	No	No
Fréon et al., 2014b	Peruvian anchoveta (*Engraulis ringens*)	1 t of fresh fish	Cradle to gate	No	No
Fréon et al., 2014c	Peruvian anchoveta (*Engraulis ringens*)	1 t of fresh fish	Cradle to gate	Mass and economic	Yes, simulations of fuel use variations of ±20% and recomputing single scores considering mass allocation.
Fréon et al., 2017	Peruvian anchoveta (*Engraulis ringens*)	(i) 1 t of fish oil or fishmeal at the gate of the plant and (ii) 1 t of raw material at the plant	(i) Cradle to gate and (ii) Gate to gate	Gross energy content, economic value and mass	Yes, cleaner production strategies: using natural gas instead of heavy fuel.
González-García et al., 2015	European pilchard (*Sardina pilchardus*)	1 t of landed pilchard	Cradle to gate	No	No
Hallstrom et al., 2019	Alaskan pollock (*Theragra chalcogramma*), Arctic char (*Salvelinus alpinus*), Cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), Atlantic salmon (*Salmo salar*), Cape hake (Merluccius capensis), Cephalopods (*Cephalopoda spp.*), European eel (*Anguilla anguilla*), European flounder (*Platichtys flesus*), Hake (*Merluccius merluccius*), Seabass (*Dicentrarchus labrax*), Sprat (*Sprattus sprattus*), Gilt-head seabream (*Sparus aurata*), Haddock (*Melanogrammus aeglefinus*), Hoki	N/A. Results of GHG emissions and nutritional score are presented as a variation of the median of the entire analysed sample.	Cradle to gate	No	Yes, variation in nutritional results when using different methods.

	(*Macruronus novaezelandiae*), Lobster (*Homarus gammarus*), Northern prawn (*Pandalus borealis*), Norway lobster (*Nephrops norvegicus*), Oyster (*Ostreidae spp.*), Pangasius (*Pangasius hypophthalmus*), Perch (*Perca fluviatilis*), Pike (*Esox lucius*), Pike-perch (*Sander lucioperca*), Pink salmon (*Oncorhynchus gorbuscha*), Plaice (*Pleuronectes platessa*), Rainbow trout (*Oncorhynchus mykiss*), Saithe (*Pollachius virens*), Scallop (*Pecten maximus*), Tilapia (*Oreochromis niloticus*), Trout (*Salmo trutta*), Turbot (*Scophthalmus maxima*), Whitefish (*Coregonus spp.*), Whiting (*Merlangius merlangus*)				
Hélias et al., 2018	Black-bellied anglerfish (*Lophius budegassa*), White anglerfish (*Lophius piscatorius*), Cod (*Gadus morhua*), Roundnose grenadier (*Coryphaenoides rupestris*), Haddock (*Melanogrammus aeglefinus*), Hake (*Merluccius merluccius*), Greenland halibut (*Reinhardtius hippoglossoides*), Herring (*Clupea harengus*), Ling (*Molva molva*), Blue ling (*Molva dypterygia*), Mackerel (*Scomber scombrus*), Horse mackerel (*Trachurus trachurus*), Megrim (*Lepidorhombus whiffiagonis*), Four-spot megrim (*Lepidorhombus boscii*), Plaice (*Pleuronectes platessa*), Beaked redfish (*Sebastes mentella*), Golden redfish (*Sebastes norvegicus*), Saithe (*Pollachius virens*), Sandeel (*Ammodytes spp.*), Seabass (*Dicentrarchus labrax*), Sole (*Solea solea*), Sprat (*Sprattus sprattus*),	N/A	N/A	No	No

	Tusk (*Brosme brosme*), Whiting (*Merlangius merlangus*) and Blue whiting (*Micromesistius poutassou*)				
Hospido and Tyedmers, 2005	Skipjack tuna (Katsuwonus pelamis) and Yellowfin tuna (*Thunnus albacares*)	1 t of frozen fish landed	Cradle to gate	No, they consider various target species within their global FU	Yes, increase and decrease fuel inputs by one standard deviation and the use of alternative emission factors from different sources.
Hospido et al., 2006	Tuna (*Thunnus albacares*)	1 t of frozen fish entering the factory	Gate to grave	Economic (for transport from retailers to households)	Yes, improvement actions: recycled percentage of packaging materials, substitution of packaging materials.
Iribarren et al., 2010a[1]	Mussel (*Mytilus galloprovincialis)*	(i) 1 kg of fresh mussels and (ii) 1 kg of canned mussels flesh	Purification/transformation and consumption stages. Excluded mussel culture and valorization of mussel organic waste and shells	Mass	No
Iribarren et al., 2010b[1]	Mussel (*Mytilus galloprovincialis*)	(i) 100 t of mussel shells and (ii) 100 t of mussel organic remains	Grave to grave: valorization of shells to calcium carbonate and organic waste to fish meal	System expansion for waste valorization	Yes, differences between current methodology of valorization (producing calcium carbonate) and others (landfilling, incineration) are considered. Also, similar differences between current organic waste valorization to fish meal and alternative production of mussel pate

					are analyzed.
Iribarren et al., 2010c[1]	Mussel (*Mytilus galloprovincialis)*	100 kg of cultured mussel: 40 kg for fresh, 35 canning, 20 frozen in cooking-freezing plants and 5 from cooking plants for cannery. For comparative effects 1 kg of fresh, canned or frozen mussel	Cradle to grave named business-to-consumer (B2C)	System expansion for waste valorization (same procedure that Iribarren et al 2010b)	Yes, regarding analysis based on 1 kg of protein supplied comparing mussels and chicken and canned tuna.
Iribarren et al., 2010d[1]	Mussel (*Mytilus galloprovincialis)*	One triple pack or rounds cans format (129 g of canned mussels, 120 g of sauce, 81 g of primary packaging and 12.73 g of secondary packaging)	Cradle to grave (B2C)	System expansion for waste valorization (same procedure that Iribarren et al 2010b)	No
Iribarren et al., 2010e	Species from coastal fishing (horse mackerel, Atlantic mackerel, European pilchard and blue whiting), offshore fishing (european hake, megrim and anglerfish), deep-sea fishing (skipjack and yellowfin tuna), extensive aquaculture (mussels) and intensive aquaculture (turbot)	1 t of fish	Cradle to gate	Economic and mass (sensitivity analysis)	Capital goods are relevant in carbon footprint results for extensive aquaculture species but not for the others.
Iribarren et al., 2011	Species from coastal fishing, offshore fishing, deep-sea fishing, extensive aquaculture and intensive aquaculture (same species that Iribarren et al 2010e)	1 t of fish	Cradle to gate	Economic and mass	Yes, based on the type of cooling agents.
Laso et al., 2016	Anchovy *(Engraulis encrasicolus)*	For heads and spines: 1 t of fish meat entering the plant.	Gate to grave.	Economic and system expansion for anchovy waste	No

		For the remaining and broken fish: 1 t paste processing		valorisation	
Laso et al., 2017a	Anchovy *(Engraulis encrasicolus)*	1 can of fish in extra virgin olive oil.	Cradle to gate (from fish to factory), gate to gate (factory process and canned products) and gate to grave (distribution and use and EoL)	System expansion for anchovy waste valorisation	Yes, different scenarios: packaging recycling is proposed -Application of BATs for canned anchovy industry such as recycle process water, recycle cardboard boxes, separate possible valorization streams, dry cleaning…
Laso et al., 2017b	Anchovy *(Engraulis encrasicolus)*	1 kg of fish entering the canning plant	Cradle to grave	System expansion, mass and economic	Yes, sensitive analysis based on mass or economic allocation.
Laso et al., 2018a	Anchovy *(Engraulis encrasicolus)*	1 kg of processed fish	Cradle to grave	System expansion	Yes, Green protein footprint according the packaging type or no packaging.
Laso et al., 2018b	Anchovy *(Engraulis encrasicolus)*	1 kg of fish	Cradle to gate	System expansion	No
Laso et al., 2018c	Anchovy *(Engraulis encrasicolus)*	1 t fish food loss (FL)	2 scenarios: Food waste-to-energy-to-food" and "Food-waste-to-food".	System expansion	No
Lourguioui et al., 2017	Mussel *(Mytilus galloprovincialis)*	1 t of mussels	Cradle to gate	No	Scenarios for mussel farms management and uncertainty analysis/Monte Carlo
Lozano et al.,2010	Mussel	1 t of mussels for each raft	Cradle to gate	No	No
Parker and Tyedmers,	Antarctic krill (*Euphausia superba*)	1 kg of krill meal 1 L of krill oil	(i) Krill meal and oil: cradle	(i) Krill meal and oil: energy	Application of three allocation scenarios to

2012a		1 consumer-ready bottle of 60 omega-3 krill oil capsules	to consumer (ii) Krill omega-3 capsules: cradle to retailer	content in fishing and primary processing (ii) Krill meal and oil: mass in transport to port (iii) Krill omega-3 capsules: system expansion in the secondary processing	omega-3 capsules. Scenario analyses of different parameters for krill meal and omega-3 capsules.
Parker and Tyedmers, 2012b	Peruvian anchovy *(Engraulis ringens)*, Atlantic herring *(Clupea harengus)*, Gulf menhaden *(Brevoortia patronus)*, blue *whiting (Micromesistius poutassou)* and Antarctic krill *(Euphausia superba)*	For each species: 100 GJ of combined meal and oil products, respecting the species-specific yields of meal and oil	N/A	Output nutritional energy of meal and oil products	Uncertainty analysis/Monte Carlo Sensitivity analysis to the FU (basis of comparison between species): ▪ 100 GJ of energy from meal and oil (baseline); ▪ 1 t of protein from meal and oil ▪ 1 t wet weight biomass
Parker et al., 2014	4 tuna species: skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacores*), albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*)	1 t of landed fish	Cradle to gate	Mass	No
Ramos et al., 2011	North East Atlantic Mackerel (NEAM) *(Scomber scombrus)*	1 t of landed round fish	Cradle to gate	Temporal allocation	No
Svanes et al., 2011	Cod *(Gadus morhua)*	1 kg cod wetpack, frozen, in 400 g packages, delivered to retailer in Sweden 1 kg cod burger, frozen, in 5 kg packages, delivered to institutional buyer in Sweden	Cod wetpack and cod burger: cradle to consumer Processed cod loin: cradle to distribution Cradle to gate (arrival at the	Mass and economic	Sensitivity analysis based on either mass and economic allocation. Scenario analyses on different parameters.

		1 kg processed cod loin product in 2 kg package, delivered to distribution centre in the UK 1 kg processing residue, frozen, going to animal feed production in Norway	processing plant)		
Van Putten et al., 2015	Tropical rock lobster (TRL, *Panulirus ornatus*) and southern rock lobster (SRL, *Jasus edwardsii*)	1 kg of lobster	Cradle to consumer	a) mass, assuming heads are wasted; b) mass, assuming heads are used; c) nutritional value (total MJ of edible product); d) economic (ex-vessel price)	Scenario analyses, using base case mass allocation on different parameters.
Thrane, 2004	Codfish, flatfish, prawn, shrimp, Norway lobster, mussels, herring, mackerel, industrial fish	1 kg of fish	Cradle to gate	System expansion and mass and economic allocation	No
Thrane, 2006	Flatfish	1 kg of frozen fish filet	Cradle to cradle	System expansion and mass and economic allocation	No
Vázquez-Rowe et al., 2010a	Atlantic horse mackerel (*Trachurus trachurus*)	1 t of round fish	Cradle to gate	Mass and economic	Yes
Vázquez-Rowe et al., 2010b	European hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), Atlantic mackerel (*Scomber scombrus*), blue whiting (*Micromesistius potassou*)	1 kg of fish	Cradle to gate	No, global catch value was considered as FU	No

Vázquez-Rowe et al., 2011a	European hake (*Merluccius merluccius*)	500 g of gutted fish fillet	Cradle to grave	Mass and economic	No
Vázquez-Rowe et al., 2011b	Broad number of vessels within selected Galician fishing fleets (target species are quite varied, depending on the gear type and geographical zone where they fish)	1 t of landed fish	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2012a	Common octopus (*Octopus vulgaris*)	24 kg of frozen octopus up to the point of import	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2013a	Hake (*Macruronus magellanicus*) fish sticks produced in a processing plant in Spain	1 package of 10 frozen fish sticks	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2013b	Hake (*Macruronus magellanicus*) fish sticks produced in a processing plant in Spain	1 package of 10 frozen fish sticks	Gate to grave	Mass	No
Vázquez-Rowe et al., 2013c	Goose barnacle (*Pollicipes pollicipes*)	1 kg of barnacles	Cradle to gate	No, due to the lack of co-products	No
Vázquez-Rowe et al. 2014a	Seafood species landed in Galician ports	1 t of fish	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2014b	European pilchard (*Sardina pilchardus*)	Amount of protein (17.26 g) supplied by one can of sardines (85.0 g) in olive oil	Cradle to gate	Mass, economic and energy	No
Villanueva-Rey et al., 2018	European pilchard (Sardina pilchardus)	1 t of fish	Cradle to gate	Mass	Yes, different assessment methods, allocation approach (economic), fishing gear life span, base port influence, engine type.
Winther et al., 2009	Norwegian seafood supply chain: a) aquaculture: Atlantic salmon (*Salmo salar*) and Blue mussels (*Mytilus edulis*); b) fishing: cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock	1 kg of edible product	Cradle to gate	Mass	Yes, different scenarios were analyzed: electricity mix, product waste, edible yield, allocation approach (economic), utilization of

	(*Melanogrammus aeglefinus*), herring (*Clupea harengus*) mackerel (*Scomber scombrus*)				processing stage by-products, feed conversion ratio, refrigerant agent, etc.
Ziegler et al., 2003	Cod (*Gadus morhua*)	400 g of fish fillets	Cradle to gate	Economic	Yes, different scenarios were considered for fishing based on fishing gear.
Ziegler and Valentinsson, 2008	Norway lobster (*Nephrops norvegicus*)	300 g of lobster tails	Cradle to gate	Economic	Yes, fuel use, allocation choice, product yield, impact assessment method and background data.
Ziegler et al., 2011	Southern pink shrimp (*Penaeus notialis*)	1 kg of shrimp	Cradle to gate	Economic	No

[1] The production of mussels (*Mytilus galloprovincialis*) in Galicia, Spain, corresponds to extensive aquaculture. However, an important auxiliary fishing fleet (1267 vessels according to the 2020 regional census) supports the cultivation of mussels in mussel rafts along the Galician rias (Pesca de Galicia, 2020).

Mass allocation was used for processed finfish (Denham et al., 2016), tuna (Avadí et al., 2014a), frozen prawn (Farmery, et al., 2005), frozen common octopus (Vazquez-Rowe et al., 2012a), and frozen hake sticks (Vazquez-Rowe et al., 2013a; Vazquez-Rowe et al., 2013b). The use of mass or economic allocation was analysed for the Galician fishing activity (Iribarren et al., 2010e; Iribarren et al., 2011) providing changes in the carbon footprint from 0.3% to 57%, denoting the importance of the allocation method.

Svanes et al. (2011) evaluated the environmental performance of cod caught by the autoline fleet in Norwegian territorial waters and its processing in four cod-derived products: wetpack, burger, loin and processing residues to animal feed. Using mass allocation, the main differences were found in the choice of whether the head was considered a co-product or a waste, while low variations were observed with economic allocation.

Economic allocation was the preferred option for packaged cod fillets (Ziegler et al., 2003) as they were dominating both in quantity and in gross sales and for Norway lobster (Ziegler and Valentinsson, 2008) and Southern pink shrimp (Ziegler et al., 2011) due to its high economic value.

Allocation based on the energy content has been traditionally downplayed as an arbitrary method that does not generally reflect the relationship between the inputs and outputs of a studied system (Ayer et al., 2007). This is common for other non-causality allocations, such as mass or economic allocation. To analyse the impact of Peruvian fishmeal or fish oil, Fréon et al. (2017) applied gross energy content, as well as economic value and mass. In addition, Parker and Tyedmers (2012a) applied allocations based on energy content, mass allocation and system expansion. This study defined three functional units: 1 kg of krill meal, 1 L of krill oil and 1 consumer-ready bottle of 60 omega-3 krill oil capsules. The authors used energy allocation for fishing and primary processing, mass allocation for transport of meal to port, and system expansion to allocate between omega-3 capsules and lower grade meal. A sensitivity analysis evaluated three allocation scenarios to omega-3 capsules: i) energy allocation for fishing and primary processing; ii) mass allocation for transport of meal to port, and iii) system expansion to allocate between omega-3 capsules and lower grade meal.

LCA practitioners may avoid allocation, if the environmental impacts are assigned to the fishing gear or the production step, instead of the species. Nevertheless, when the species and by-products are considered, it is first recommended to expand the boundaries of the system prior to allocation and, if possible, use both mass and economic allocation for the same case study in order to compare approaches. Generally, mass allocation gives initial accuracy on data (widely known) if the energy content of all species is within the same range. If the variability in nutrient content of the species landed is high or will be transformed into sub-products (e.g., fish oil), energy allocation is suggested (Avadí and Fréon, 2013) together with the use of economic variables. However, as mentioned above, sometimes this information is not available and is strongly influenced by market fluctuations.

3.1.4 Sensitivity analysis

When sensitivity analysis was conducted for the studies reviewed mainly discussed the fuel use of vessels (Avadí et al., 2015, 2018; Fréon et al., 2014c; Hospido and Tyedmers, 2005), packaging and cleaner production strategies. Although the manufacture of primary packaging for marine products is not the main contributor to the total environmental impact along it's life cycle (Molina-Besch, 2016), several authors evaluated the kind of material and the recycling percentage of the packaging material used (Almeida et al., 2015; Avadí et al., 2014a, 2015; Hospido et al., 2006).

Linked to cleaner production strategies, Laso et al. (2017a) proposed some BATs for canned anchovy industry, such as reuse of process water, recycling of cardboard boxes, separate possible valorisation streams or dry cleaning. Other authors also applied sensitivity analysis for BATs. For instance, Avadí et al. (2014a) and Driscoll et al. (2015) evaluated the use of electricity and, concretely, Denham et al. (2016), focused on solar electricity and biogas electricity, and other scenarios such as the reduction of greenhouse gas (GHG) emissions from refrigeration and utilizing waste to develop by-products. Meanwhile, Iribarren et al. (2010b) considered differences between current methodology of mussel valorisation (producing calcium carbonate) and others (landfilling, incineration) and concluded that the contribution of environmental impacts coming from valorisation processes are lower compared to mussel culture, fresh mussel purification or mussel transformation in cannery factories.

Finally, some studies collected the impacts of the fishing gear (Almeida et al., 2014; Driscoll and Tyedmers, 2010; Ziegler et al., 2003), catch variation (Driscoll and Tyedmers, 2010; Farmery et al., 2015), or multiple variables. For instance, Abdou et al. (2020) addressed management scenarios, varying the marine protected areas or the extension of the biological rest period, as well as evaluated a decrease in the number of demersal trawlers (Abdou et al., 2020). Driscoll et al. (2015) studied the reduction of refrigerant leakage of the fishing fleet, the fuel consumption to wetpack and the use of energy, packaging and water, and the increment of gutted fish parts to human consumption. Winther et al. (2009) discussed electricity mix, product waste, edible yield, by-products and refrigerant agents.

3.2. Life cycle impact assessment (LCIA)

Regarding life cycle impact assessment (LCIA) methods, CML-IA (Guinée et al., 2001) was the most widely used representing approximately 50% of the studies reviewed. There was a marked decline in the use of its versions (2000, 2001 and 2002), as evident in Table 3. The impact categories included in this method are those used in many LCA studies. The baseline indicators, which are the standard, are based on the best practice principle available and are category indicators at the outcome level (also referred to as the problem-oriented approach). LCA practitioners rarely applied the non-baseline, which addresses 11 impact categories in CML 2001, disaggregated into 50 subcategories, against the 8 general impact categories of the baseline (acidification, climate change, depletion of abiotic resources, ecotoxicity, eutrophication, human toxicity, ozone layer depletion and photochemical oxidation).

Likewise, more recent assessment methods were applied, such as ReCiPe (Huijbregts et al., 2017) that was implemented in approximately 25% of the publications analysed. This method can be described as an update and combination of 18 midpoint indicators of the CML 2001 and the three endpoint indicators (i.e., damage to human health, ecosystem quality, and resource availability) of the Ecoindicator 99 methodologies. In addition, utilization of other assessment methods addressing specific impacts, such as the carbon footprint that was updated through the 2001, 2007 and 2013 versions of the IPCC, the PAS 2050 British specification published in 2008 (Iribarren et al., 2010e, 2010e, 2011), and the GHGs emission factors (Denham et al., 2016; Driscoll and Tyedmers, 2010; Hallstrom et al., 2019); or the energy consumption through the Cumulative Energy Demand (CED) (Vázquez-Rowe et al. 2014a), aiming at energy return on investment (EROI) calculation.

Some of the aforementioned methods were used for the same studies, or in combination with others. For instance, UseTox, developed under the United Nations Environment Program and the Society for Environmental Toxicology and Chemistry Life Cycle Initiative (UNEP-SETAC) (Rosenbaum, 2008), was applied together with ICLM and ReCiPe to evaluate the air, agricultural soil, natural soil, freshwater and seawater dimension of the impacts (Avadí et al., 2014a; Avadí and Fréon, 2015; Fréon et al., 2014b), while the ILCD recommendation (European Commission, 2011) was also implemented with ReCiPe and CED by Winther et al. (2009).

3.2.1. Impact categories in LCIA

Almost 50 impact categories indicators were found in the 59 studies reviewed (see Supplementary Material). However, several indicators refer to the same environmental mechanism impact (midpoint) or damage (endpoint). In order to simplify the analysis, we were able to identify 17 types of impacts analysed by the papers, which can be computed by different methods: climate change, indicator of potential global warming due to GHG emissions; ozone depletion, for air emissions destroying the stratospheric ozone layer; photochemical oxidant formation, focused on the photochemical ozone created in the lower atmosphere (smog) catalysed by sunlight; particulate matter formation, for assessing damage to human health due to primary PM2.5 and PM2.5 precursor emissions; ionizing radiation, related to the damage that emissions of radionuclides produce in human health and ecosystems; acidification, of soils and water due to the release of gases such as nitrogen and sulphur oxides; eutrophication, measuring the abnormal nutrient enrichment of aquatic ecosystems due to nitrogen or phosphor containing compounds; ecotoxicity, which evaluates the toxic emissions on freshwater, sea water or land ; human toxicity, based on the potential harm of emitted substances in people; land use, addressing the damage for occupation; abiotic depletion, referred to the consumption of non-biological resources; water use; and energy demand, indicator to quantify the primary energy usage (Acero et al., 2017).

Table 2 shows this classification and to which acronym the impact categories type refer (for: CML-IA, ReCiPe, ESA/IChemE). It also shows the number of studies (and the associated percentage) that consider each type of impact. The detail of the main impact categories studied in each study is shown in Table 3. These LCIA indicators also involved more than 20 indicators related to specific issues (specific to fisheries or socio-economic topics) that are discussed in the section 3.3.2.

Table 2. Frequency of LCIA impact categories and methods application in the reviewed studies

Impact categories	CML-IA	ReCiPe	ESA IChemE	Others methods/ indicators	N studies	%
Climate change	GWP	CC	GWP	-	54	86%
Ozone depletion	ODP	OD	SOD	-	31	49%
Photochemical oxidant formation	POFP	POF	POF	-	25	40%
Particulate matter formation	-	PMF	-	-	8	13%
Ionizing radiation	-	IR	-	-	6	10%
Acidification	AP	TA	AA	-	38	60%
Eutrophication	EP	FE, ME	E, AOD	-	39	62%
Ecotoxicity	METP, TETP	TE, FE, MET	EAL, EAL2	-	27	43%
Human toxicity	HTP	HT	-	-	19	30%
Land use	LOP	ALO, ULO,	-	-	13	21%

		NLT				
Abiotic depletion	ADP	MD, FD	-	-	24	38%
Water use	-	WD	-	-	10	16%
Energy demand	-	-	-	CED, TCED, EU	27	43%
Biotic (fish) resources use	-	-	-	see detailed analysis	22	37%
Nutritional impact	-	-	-	see detailed analysis	7	12%
Sea-bed damage	-	-	-	see detailed analysis	1	2%
Socio-economic	-	-	-	see detailed analysis	3	5%

GWP: Global Warming Potential; CC: Climate Change; ODP: Ozone Depletion Potential; OD: Ozone Depletion; SOD: Stratospheric Ozone Depletion; POFP: Photochemical Oxidant Formation Potential; POF: Photochemical Oxidant formation; PMF: Particulate matter formation; IR: Ionizing radiation; AP: Acidification Potential; TA: Terrestrial acidification; AA: Atmospheric acidification; EP: Eutrophication Potential; FE: Freshwater eutrophication; ME: Marine eutrophication; E: Eutrophication; AOD: Aquatic oxygen demand; METP: Marine Eco-Toxicity Potential; TETP: Terrestrial Eco-Toxicity Potential; TE: Terrestrial ecotoxicity; FE: Freshwater ecotoxicity; MET: Marine ecotoxicity; EAL: Ecotoxicity to aquatic life (metals to seawater); EAL2: Ecotoxicity to aquatic life (other substances); HTP: Human Toxicity Potential; HT: Human toxicity; LOP: Land Occupation Potential; ALO: Agricultural land occupation; ULO: Urban land occupation; NLT: Natural land transformation; ADP: Abiotic Depletion Potential; MD: Metal depletion; FD: Fossil depletion; WD: Water depletion; CED: Cumulative energy demand; TCED: Total Cumulative Energy Demand; EU: Energy use.

Table 3. Impact categories per study.

		Typical LCIA indicators												LCI	Fishery specific			
Study	**LCIA Method**	**Climate change**	**Ozone depletion**	**Photochemical oxidant formation**	**Particlaute matter formation**	**Ionizing radiation**	**Acidification**	**Eutrophication**	**Ecotoxicity**	**Human toxicity**	**Land use**	**Abiotic depletion**	**Water use**	**Energyu demand**	Biotic (fish) resources use	Sea use	Nutritional	Socio-economic
Abdou et al., 2018	CML baseline 2000	X	X	X			X	X	X	X	X	X		X	X	X		
Abdou et al., 2020	Ecopath with Ecosim (EWE)	X	X	X			X	X	X	X	X	X		X	X			
Almeida et al., 2014	CML baseline 2 2002	X	X				X	X						X	X			
Almeida et al., 2015	CML-IA baseline	X	X	X			X	X	X			X		X				
Avadí et al., 2014a	ReCIPE, CML baseline 2000 and USEtox	X					X	X		X	X	X	X	X	X			
Avadí et al., 2014b	ReCIPE	X	X	X	X	X	X	X	X	X	X	X	X					
Avadí et al., 2015	ReCiPe	X		X	X			X		X		X		X				
Avadí and Fréon, 2015	ReCIPE, CML-IA baseline 2000 and USEtox	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X
Avadí et al., 2018	ReCiPe	X		X	X			X	X	X	X	X	X	X	X			
Denham et al. 2016	GHGs emission factors	X																
Driscoll and Tyedmers, 2010	GHGs emission factors	X													X			
Driscoll et al., 2015	CML baseline 2 2000	X	X				X					X		X	X			
Farmery et al., 2015	Australian impact method	X						X	X				X	X	X			

Fréon et al., 2010	N/A																	X
Fréon et al., 2014b	ReCiPe, USETox, CML 2000 and 2001	X	X	X	X	X	X	X	X	X	X	X	X					
Fréon et al., 2014c	ReCiPe	X					X	X						X	X			X
Fréon et al. 2017	ReCiPe	X	X	X	X	X	X	X	X	X	X	X	X					
González-García, 2015	ReCiPe	X																
Hallstrom et al., 2019	GHGs emission factors	X																
Hélias et al., 2018	N/A														X			
Hospido and Tyedmers, 2005	CML baseline	X	X	X			X		X	X								
Hospido et al., 2006	CML baseline	X	X	X			X	X				X						
Iribarren et al., 2010a	CML 2000	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010b	CML 2001	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010c	CML 2001	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010d	PAS 2050 and IPCC, 2007.	X																
Iribarren et al., 2010e	PAS 2050 and IPCC, 2007.	X																
Iribarren et al., 2011	PAS 2050 and IPCC, 2007.	X																
Laso et al., 2016	ESA with metrics from IChemE 2002.	X	X				X	X	X									
Laso et al., 2017a	ESA with metrics from IChemE 2002.	X	X				X	X	X									
Laso et al., 2017b	ESA with metrics from IChemE 2002.	X	X				X	X	X									
Laso et al., 2018a	JRC of EC. IPCC, 2013, ReCiPe, CML-IA	X					X	X										
Laso et al., 2018b	JRC of EC. ReCiPe, CML-IA	X					X	X										
Laso et al., 2018c	IPCC, 2013 and specific calculations	X											X	X			X	
Lourguioui et al., 2017	CML baseline 2000	X					X	X						X				
Lozano et al., 2010	CML baseline 2000	X	X	X			X	X	X	X		X			X			
Parker and Tyedmers, 2012a	CML 2 baseline 2000	X	X				X	X						X	X			
Parker and Tyedmers, 2012b	Marine footprint														X			
Parker et al., 2014	IPCC 2007 characterization factors	X												X	X			
Ramos et al., 2011	CML baseline 2000	X	X				X	X	X			X						
Van Putten et al., 2016	CML baseline 2000	X	X				X	X						X				
Svanes et al., 2011	CML 2 baseline 2000	X	X	X			X	X						X				
Thrane, 2004	ISO 14040-43													X	X	X		
Thrane, 2006	Danish EDIP 97	X	X	X			X	X	X	X				X				
Vázquez-Rowe et al., 2010a	CML baseline 2000	X	X	X			X	X	X	X		X						
Vázquez-Rowe et al., 2010b	CML baseline 2000	X	X	X			X	X				X						
Vázquez-Rowe et al., 2011a	CML baseline 2000	X	X				X	X	X			X			X			
Vázquez-Rowe et al., 2011b	EMEP Corinair, CML baseline 2000	X					X	X	X			X		X				

Vázquez-Rowe et al. 2012a	CML baseline 2000	X	X	X			X	X	X			X			X	X		
Vázquez-Rowe et al. 2013a	IPCC 2001	X												X				
Vázquez-Rowe et al. 2013b	IPCC 2001	X																
Vázquez-Rowe et al. 2013c	IPCC 2001	X												X				
Vázquez-Rowe et al. 2014a	Cumulative Energy Demand													X				
Vázquez-Rowe et al. 2014b	ReCiPe	X	X	X	X	X	X	X	X	X	X	X	X		X	X		
Villanueva-Rey, 2018	ILCD, ReCiPe, CED	X	X	X	X	X	X	X	X	X	X	X	X	X				
Winther et al., 2009	IPCC 2007; CED	X												X				
Ziegler et al., 2003	CML baseline 2001	X		X			X	X						X	X	X		
Ziegler and Valentinsson, 2008	CML baseline 2001, Ecoindicator 99	X	X	X			X	X	X						X	X		
Ziegler et al., 2011	CML baseline 2 2000	X	X	X			X	X	X	X				X	X	X		
	Number of studies	54	31	25	8	6	38	39	27	19	13	24	10	27	22	7	1	3
	%	92%	53%	42%	14%	10%	64%	66%	46%	32%	22%	41%	17%	46%	37%	12%	2%	5%

Focusing on emission related impacts, 54 studies (92%) computed climate change impacts as it constituted the most scrutinized impact in LCA. It should be noted that 6 studies measured carbon footprint exclusively and, therefore, only assessed climate change impacts. Ozone depletion (53%), photochemical oxidant formation (42%), acidification (64%), eutrophication (66%) and ecotoxicity (46%) were the 5 next most represented impact categories that were computed in most of the LCIA methods reviewed. Surprisingly, human toxicity impact category was only found in 32% of the studies reviewed, despite the fact that it is included in most of LCIA methods. The lack of consensus behind this impact category due to the uncertainty and variability related to both the health and ecotoxic effect data or the limited data on bioconcentration factors for fish or chemical degradation rates, among other parameters, could be one of the main reasons explaining its underrepresentation in the sample assessed (Rosenbaum, 2008). Finally, the two other emission-related impact categories, namely particulate matter formation and ionizing radiation, were found in only 14% and 10% of the studies, respectively. Such impact categories could be of interest for the fishery and seafood sector, more singularly particulate matter formation due to the influence of fishing boats to the ambient air and human health near the coast (Zhang et al., 2018).

Impact categories related to resource use and energy indicators were less represented in the studies reviewed. Abiotic depletion (including fossil and metal) and land use categories were found in 41% and 22% of the studies, respectively. Water use related impacts were computed in only 17% of the studies, which can be justified by the fact that methodology development in this field is recent. Indeed, the water foot printing was coined as “virtual water” in 1997, later renamed to the current terminology at the beginning of the millennium and finally adopted in the LCIA methodologies in 2010s (Pfister et al., 2017). Specific biotic resources use and sea use impact categories for fisheries have been applied in the reviewed papers and are more specifically analysed in the section 3.3.2. Notwithstanding this, energy demand indicators are assessed in nearly half of the studies (46%). Even if such indicators are not part of LCIA methods as they are rather synthetic LCI indicators, it highlights that they are frequently used as complementary information.

Recent publications that describe the use of up to date and innovative methodologies, such as ReCiPe, suggests that it is worth including a large set of environmental impacts that may be of importance for the fisheries sector. This would also enable the computation of endpoint damage and would provide synthetized information. Modelling of endpoint damages was found in 8 studies (Laso et al., 2018; Vazquez-Rowe et al., 2014; Avadí and Fréon, 2015; Avadí et al., 2014a; Avadí et al., 2014b; Fréon et al., 2014; Gonzalez-Garcia et al., 2015) using ReCiPe. ReCiPe aggregates 18 midpoint impact categories in three endpoint damage categories or areas of protection, namely human health, ecosystem quality and resources. These 8 studies also compute single score that weights and normalizes the three areas of protection. Studies highlight the benefit of single score for communication, however, the large uncertainty associated with such metrics was evident in some studies (Laso et al., 2018).

Another trend in LCIA is the regionalization of impacts in order to better represent site-specific environmental interventions (Patouillard et al., 2017). This may enhance the relevance of LCIA for seafood products because they usually generate direct impacts that are space dependant (e.g., impacts associated to toxic or eutrophying substances emitted in the marine environment or to water use in the supply chain). However, none of the reviewed studies used spatially differentiated LCIA methodologies (such as LC-Impact (Verones et al., 2020)), as they are too recent and not yet implemented in LCA software.

3.2.2. Fishery-specific impacts categories

Other impact categories related to the fish and seafood sector are assessed in the studies reviewed. Although this kind of indicators were rarely the main target of studies, 25 different indicators related to biotic (fish) resource, sea use, nutritional and socio-economic approaches were analysed (see Supplementary Material).

Impacts related to the removal of fish stocks have been estimated by several different indicators in 37% of the studies reviewed. A significant number of studies assesses this impact given that overfishing ranks as one the most important threat to biodiversity loss in global marine ecosystems (Millennium Ecosystem Assessment, 2005; Emanuelsson et al., 2014). Such indicators include mean trophic index, lost potential yield, biotic natural resources index, discards and fish biomass extraction, among others. Avadí and Fréon (2013) already extensively discuss these indicators and their relevance, indicating that most of them are stand-alone indicators that are not part of LCIA methods. The diversity of indicators used shows the importance of setting up consensual or harmonized indicators to address the challenge of biotic resource use, a task that has been led by the Life Cycle Initiative through its Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) project (LCI, 2020). It should be noted that there have been attempts to better integrate such indicators in LCIA framework, leading to natural resources area of protection (Hélias et al., 2018; Hélias and Heijungs, 2019)

Seabed damage is also a predominant driver for biodiversity loss in oceans worldwide (Millennium Ecosystem Assessment, 2005; Woods and Verones, 2019). Twelve percent of the studies consider this impact with various indicators that are discussed in Avadí and Fréon (2013) and Woods et al. (2016). Meanwhile, only one study considers nutritional indicator, through the use of protein content (Laso et al., 2018c). Nutritional impacts are more and more assessed in LCA of food and new methods are being developed in this area (Stylianou et al., 2016). Phase 3 of GLAM should focus on biotic resources and nutritional impact and therefore give guidance to the fishery and seafood sectors to address these important impact and damage categories (UNEP, 2020). Moreover, Woods et al. (2016) recommend the inclusion of (over)exploitation of fish and seabed damage in order to have a meaningful assessment of marine ecological impacts in LCA.

Other pathways recommended by Woods et al. (2016) include marine plastic debris related impacts. This was not found in the reviewed papers whereas fisheries can contribute to this impact category. This is because no operational methods exist yet to integrate such impacts in LCA. New methods are being developed in the frame of the Marine Impacts in Life Cycle Assessment initiative (MarILCA, 2020), following the call of the Medellin Declaration to develop new impact pathways to account for this environmental hazard (Sonneman and Valdivia, 2017).

LCA traditionally focuses on the evaluation of the environmental impacts of processes or products. Thus, discussion of socio-economic issues has been minimal in the context of fisheries LCA literature (Pelletier et al., 2007). All of the 59 reviewed studies focus on environmental impacts of production systems, and only three address socio-economic indicators in fishery-specific impacts categories. Yet, in order to address sustainability objectives, assessments need to consider not only environmental aspects but also social and economic impacts (Kruse et al., 2008).

Avadí and Fréon (2015) proposed to complete LCA indicators with a set of other indicators to evaluate the sustainability performance of anchoveta fisheries and freshwater aquaculture industries. The set included nutritional profiling, energy and socio-economic assessments. The socio-economic indicators include production costs, added value, gross profit generation and employment. This approach allows accurate comparisons of different products by bringing an added value to LCA and gives a concrete perspective of sustainability by incorporating the social and economic perspectives together with the environmental one.

Other life cycle methods, namely Social LCA (SLCA) and Life Cycle Costing (LCC), have been developed as necessary complements for capturing trade-offs between environmental, social and economic aspects along the life cycle of production systems (Dreyer et al., 2006; Guinée et al., 2011). For instance, Soltanpour et al. (2020) used SLCA to analyse a case of fisheries management. However, SLCA approaches show that the perception of social impacts is highly variable, and the methodology is often debated, in particular regarding data frames (Jørgensen et al., 2008). Moreover, the Life Cycle Sustainability Assessment (LCSA) framework combines LCA, SLCA and LCC. LCSA evaluates environmental, social and economic negative impacts and benefits on decision-making processes towards more sustainable products throughout their life cycle (Valdivia et al., 2013). LCSA has also been applied to fisheries management research. For instance, Kruse et al. (2008) attempted to apply this approach in a seafood context.

Beyond life cycle methods, a great variety of system analysis tools have been developed, focusing on diverse types of impacts and dimensions of sustainability. Some of those methods could complement fisheries LCAs for wider, more holistic studies (Avadí and Fréon, 2013). By using an input-output model to test the socio-economic impacts on a few case studies in the Atlantic coast, the Interreg Neptunus project will also study economic implications of seafood circular economy, as well as economic benefits and drawbacks of implementing actions for proposed strategies under a circular and NEXUS eco-labelling approach (Neptunus, 2020). There is also scope to assign risk assessment categories for input-outputs model that will contribute to LCA knolwedge for seafood sector as described recently by Tahar et al. (2017) who focused on the waste water industry.

3.3. Seafood LCA practitioners: who and why

From the revision of the LCA studies, the location of the research institutions involved and the species studied offers a good overview of the investigation on seafood. Figure 4 qualitatively represents the geographic distribution of the authorship of the studies per country and fishing ground (area from which the studied species are caught). Most of the research was carried out by one or several institutions from only one territory, while 14 had international collaboration and involved researchers from two to four different countries. Geographically, Europe concentrates the largest number of research centres practicing LCA, constituting the FAO fishing area 27 and the most evaluated oceanid territory (FAO, 2015). Institutions from Spain participated in 33 studies collected in this review, followed by France and Peru (9 each), Sweden (6), Canada (5), Australia (4), Denmark and Portugal (3 each), Norway, Tunisia and United States of America (2 each) and, finally, Algeria, Ecuador, Italy, Luxembourg, Switzerland and United Kingdom (1 each). Regarding the fishing zones or waters, LCA studies in the 2000s focused on Atlantic and Pacific fisheries (Vázquez-Rowe et al., 2012b). However, to date, almost all major waters have been part of at least one article including -Mediterranean, Caribbean, Baltic, Tasman or North seas- but excluding, for instance, the Black or Caspian seas and Eastern Asia. This is notable as Asia is the largest worldwide fish producer: China remains a major fish producer, accounting for 35 percent of global fish production (FAO 2020). Although numerous studies on aquaculture LCA have been also published in Asia in recent years (Henriksson et al., 2018; Jarvio et al., 2018). It's appreciated that LCA typically remains a Western tool in this field of study, which is probably due to the higher environmental requirements for food production in European countries and others belonging to the Organization for Economic Co-operation and Development (EOCD, 2020). This unbalanced distribution can also be related with persistent differences in fish consumption levels. In developed countries the apparent fish consumption is 26.4 kg, 22% above global average (20.5 kg) while in developing countries it is considerably lower, 19.4 kg (FAO 2020).

With respect to the analysed species, most studies focused on a single species or several similar species (Hospido and Tyedmers, 2005; Parker et al., 2014; Avadí et al., 2015). Typically, these species are emblematic of the regions analysed, such as anchovy in Peru (Fréon et al., 2010, 2014a, 2014b, 2014c, 2017) and Cantabria (Laso et al., 2016, 2017a, 2017b, 2018a, 2018b, 2018c), mussels in Galicia (Barros et al., 2009; Iribarren 2010a, 2010b, 2010c, 2010d), pilchard in Portugal (Almeida et al., 2014, 2015; González-García et al., 2015), white banana prawn in Australia (Farmery et al., 2015) or lobster in the United States (Driscoll et al., 2015). Few authors addressed the analysis of multiple species in the same study (Parker and Tyedmers, 2012b; Vázquez-Rowe et al., 2012b; Hélias et al., 2018; Avadí et al., 2019) and some included species from coastal fishing, offshore fishing, deep-sea fishing, extensive aquaculture and intensive aquaculture (Iribarren 2010e, 2011; Winther et al., 2009; Avadí and Fréon, 2015).

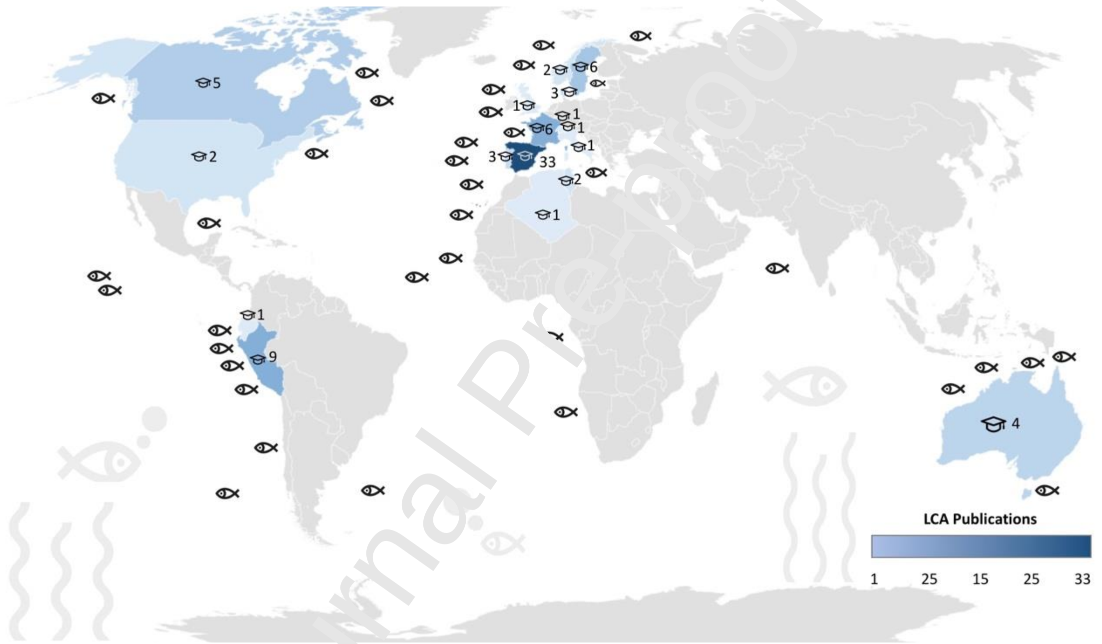

Figure 4. Geographic distribution of LCA publications per country (cap) and fishing ground (fish). The most intense colour in a territory indicates the largest number of studies.

Almost all studies have been conducted by public bodies, such as universities, institutes and schools with the purpose of characterizing the seafood sector to address the potential environmental impact of the seafood supply chain, from fishing through processing up to consumers, as well as to identify hotspots and evaluate improvement opportunities to promote the sustainability of this part of the Blue economy. Research focused on evaluating the marine species stock, eventual increase of the wild-caught fishery, potential expansion of aquaculture, ecolabelling, effects of climate change in ocean ecosystems, and use of different fishing gears were issues that were the topic in these LCA studies. In contrast, very few LCA articles shared authorship with private companies, industries or consultancies (Laso et al., 2017a, 2017b, 2018a, 2018b, 2018c; Avadí et al., 2018). Only one research article was attributed to industry, which analysed and compared (with competing products from EU market) the carbon and energy footprint of Norwegian seafood supply chain (Winther et al., 2009). The remaining studies were developed by LCA practitioners in research centres from a theoretical perpsective based on direct enquiries to stakeholder and producers, official inventories, and so forth. This is probably due to scientific interest as the public and/or market relevance in their countries; or simply, ease of data collection.

The scientific and technical knowledge of some papers provides valuable inputs for fishery management and future regulations (Ziegler et al., 2016; Villanueva-Rey et al., 2018). For instance, fuel use and packaging in canning products were identified as important shortcomings to be addressed in the extraction and processing phases, respectively. These implications may guide policymakers and stakeholders about where best to make improvements that will lead to sustaining processes and design strategies, including behavioural change. Moreover, several papers promoted new approaches for the first time including 'geographically' focusing on LCA for aquaculture (Lourguioui et al., 2017) and fisheries (Abdou et al., 2018) in the Mediterranean or making a comprehensive LCA of the entire Peruvian anchovy fleet (Freón et al., 2014b). Other studies report on the ''timely' development of the first fishery LCA study with inventory data for the period 2001 to 2008 (Ramos et al., 2011; Almeida et al., 2014). 'Technically', the first LCA study of fishmeal plants considered construction and maintenance phases (Freón et al., 2017) or applying the 'water-energy-food-climate nexus'' index to a case study for fisheries (Laso et al., 2018c). ''Managerially', the first ecolabel in the Spanish fishing sector has been based on life cycle approaches for seafood products (Vázquez-Rowe et al., 2016).

3.4. Nexus water-energy-food in the seafood sector

The assessment of individual environmental impact categories in LCA offers high added-value information, such as providing insights for further improvements in processes, products and services, as well as support in policy-making and environmental certification schemes. However, such an assessment gives a perspective that is circumscribed to the link between each impact category and the specific environmental problem that it represents. Although in some cases the environmental impacts of these impact categories are aggregated in endpoint damage indicators, which provide a more direct connection with the tecnosphere and the environment, in the case of seafood LCA studies, as mentioned above, these were only applied in 8 studies. Moreover, even the computation of endpoint damages with current

LCIA methods lacks a strong interconnection between variables to reach robust results that allow a holistic analysis of production systems.

In this context, the nexus approach arises as a perspective that recognizes the fact that water, energy, food production systems (in this case, wild fish capture) and natural ecosystems show a series of robust and indivisible multi-dimensional interlinkages. We argue that when referring to life cycle studies in the seafood sector, nexus thinking is needed to appropriately transition to a circular economy (Ruiz-Salmon et al., 2020). This is essentially a transformative approach to governance, and also requires substantial changes in individual behavior. Therefore, the nexus implies how to govern such transformations, and the policy tools that will be required, including behavioral change interventions that go beyond mere education to influence how people make decisions regarding the purchase and consumption of marine products. In contrast, a traditional fragmented approach, that obviates this nexus perspective while attempting to achieve resource security independently, will not only generate sub-optimal outcomes, but may also endanger food security and sustainability (Staupe-Delgado, 2020).

Water, energy and food are basic requirements for everyday life and are key activities advancing the seafood sector. In this sense, the lack of a secure and economical provision of one of them might lead to disruption in the supply and accessibility of the two others (Machell et al., 2015). Thus, the application of a water-energy-food nexus under a holistic approach appears to cover the gap of the isolated impact categories aforementioned. LCA is particularly important for understanding the interconnections in the nexus, as it enables the consideration of entire supply chains. In fact, Hamiche et al. (2016) highlighted LCA as a valuable tool to shed light on the links between the water and energy sectors, since it is able to account for direct and indirect consumption. Similarly, De Laurentiis et al. (2016) and Mannan et al. (2018) also considered LCA as the best available tool to enable the developing of the nexus framework, driving the shift towards sustainable food systems thereby.

Having said this, a nexus approach using life cycle methods would have to redefine the selection of environmental impact categories that are traditionally used (see Table 3). For instance, the quantification of freshwater consumption by the seafood sector has received little attention (Vanham, 2016). This is remarkable considering that freshwater aquaculture, as well as fish processing in general, is a water-intensive industry and a large discharge of organic material. Therefore, we consider that new water consumption metrics, currently available in LCIA methods (e.g., AWARE), as well as a wider array of water degradation categories should be included in seafood LCA studies in order to enhance the meaningfulness of these under a nexus approach. Moreover, this would allow determining whether the planetary boundary of freshwater use is below its breaching risk in the studies conducted, ensuring, this way, clean, affordable and accessible energy generation and sustainable freshwater consumption to support food supply (Steffen et al., 2015).

In terms of energy, it must be noted that a high correlation exists between food and energy prices. This connection is even more pronounced for intensive capture fisheries, which are usually fully dependent on fossil fuels (Parker and Tyedmers, 2015). In contrast to water, energy has been repeatedly reported and included in seafood LCA studies, directly, through the use of the CED impact category or the EROI indicator, or indirectly, by monitoring environmental impacts that are heavily dependent on energy intensity (Weidema et al., 2008).

Finally, focusing on the food component of the nexus, seafood products are widely accepted to be an essential component of a balanced and healthy diet because they have a high "good fat" content and provide high quality proteins and many micronutrients, such as vitamins and minerals (Larsen et al., 2011; WHO, 2020). For instance, the NRF9.3 score, i.e., a nutritional index based on 9 nutrients to encourage and 3 nutrients to limit (Drewnowski, 2009) has been combined in the literature with LCA, mainly from a human diet perspective, in an effort to analyzed the sustainability of diets across the world and determine, through linear programming or other methods (Vázquez-Rowe et al., 2019; Larrea-Gallegos and Vázquez-Rowe, 2020), future healthy diets. In this context, Castañé and Antón (2017) identified a considerable environmental impact due to a high global warming potential per kg of seafood produced due to energy consumption, but no details were given on the specific seafood products that were included in the assessment. Similarly, some attempts have been made to include a ranking for fish species based on nutrient density, climate impact and their combination (Hallström et al., 2019), but the nexus between the potential of the nutrients from seafood and environment effects is yet to be deeply researched.

Overall, the nexus approach can support the identification of synergies and trade-offs between water and energy systems and food systems aiming at resources efficiency and environmental impacts –production and consumption— reduction (Mannan et al., 2018). Advancements towards a greater linkage between terrestrial and marine systems, however, are necessary for fishing activities within a nexus framework. Freshwater consumption should be considered throughout the full supply chain of seafood products (Gephart et al., 2017; Vanham, 2016), as well as energy consumption produced by water resources (D'Odorico et al., 2018). The water dimension of the nexus should consider the water used during on-board activities (e.g. ice and water) and on-land activities where several processing activities consume freshwater and use energy produced by water resources (Gephart et al., 2017; Vanham, 2016). Some of the freshwater used in these processing activities can result in wastewater that, in turn, also consumes energy for its treatment (Vanham, 2016). Furthermore, there are also seafood processed-derived products that use crop ingredients (Vázquez-Rowe et al., 2013a), which, in turn, also consume freshwater that needs to be accounted for (Salmoral and Yan, 2018). Moreover, within a global context of increasing population and growth of water and energy use, the production, consumption and waste of food raises social questions, such as global food insecurity, food prices and international food shortages. Consequently, reducing food losses and waste is necessary to meet forecasted nutritional needs and to enhance the link with the energy and water implications.

All in all, a standardization for the nexus variable which defines, evaluates and modifies future strategies is lacking. The existence of this framework would allow the analysis of the interacting governing forces and balance the nutritional, economic and energetic value of the seafood sector to foster informed decisions, engaging industry stakeholders and consumers. Thus, the development of a unified water-energy-food nexus framework (Endo et al., 2015) would address the opportunity to strengthen the social, economic and environmental aspects of this specific but worldwide system. Furthermore, the nexus also helps international policies and scientific researchers to better adapt local and regional commerce for new perspectives. Finally, there are clear links between the SDGs of the Agenda 2030 of the UN and the water-energy-food nexus. Hence, this nexus can support the achievement of the SDGs when taking a transdisciplinary approach (Ghodsvali et al., 2019).

3.5. Challenges and opportunities for LCA in the seafood sector

The application of LCA in the broader seafood sector presents a number of key challenges and opportunities, which in many cases are related to the circular economy and the management of process waste streams. Some of the most pressing challenges facing the sector are the: (i) proliferation of marine debris comprised of plastics and other artificial materials (Maximenko et al., 2019); (ii) generation of waste and its valorisation, and (iii) climate change (Ruiz-Salmón et al., 2020). These are challenges that LCA can help address in particular when evaluating the nature of the challenge, analysing how various parts of the seafood sector contribute to these issues and identifying where targeted improvements to the sector can yield most sustainability gains while transitioning to a CE.

3.5.1 Marine debris

It is estimated that there are 120 million tonnes of plastic in the oceans and between 11.6 – 21.1 tonnes in the Atlantic Ocean alone (Jambeck et al., 2015; Pabortsava and Lampitt, 2020). These plastics are non-biodegradable and breakdown into smaller pieces due to weakening by ultraviolet light and the motion of the ocean. They can impact on marine wildlife and trophic levels, where organisms mistake the plastics for food resulting in ingestion which may cause physical impairment or death (Maximenko et al., 2019; Provencher et al., 2018). The use of additional substances (e.g. colorants and stabilisers) in the production of these plastics, may make them toxic, further exacerbating their impacts. There remains, however, a significant gap of knowledge in the understanding of these toxicological and ecotoxicological impacts. Derelict and lost fishing gear, as well as shipwrecks, is the archetype of how seafood supply chains and processes can contribute to marine debris. It is estimated that lost gear makes up 46% of the Great Pacific Garbage Patch (Lebreton et al., 2018; Maximenko et al., 2019). As well as contributing to marine debris, lost fishing gear, commonly referred to as ghost nets, can continue to capture and kill fish and other organisms for many years after being lost. While switching to biodegradable nets is being evaluated, it has been reported that these nets may have a lower catch efficiency when compared to conventional nylon nets (Grimaldo et al., 2019). These losses in efficiency and a possible increase in fishing effort to offset this loss, is something which would benefit from an LCA perspective, particularly with regard to changes related to fuel use, the largest contributor to the impacts (Avadí et al., 2019), but also in other inventory items, such as refrigerating agents (Vázquez-Rowe et al., 2012a).

While the impact of ghost fishing (Vázquez-Rowe et al., 2012c) and seabed disturbance (Woods and Verones, 2019) has been described in some fishery LCA studies, current LCIA methods do not consider certain marine environmental impacts, such as biotic depletion or the degradation of the marine environment due to plastics accumulation in the ocean or damage to seafloor (Avadí et al., 2019), despite certain methodological advancement in recent years (Hélias et al., 2018). Furthermore, there is concern over the trophic transfer of these substances due to bioaccumulation and biomagnification (Maximenko et al., 2019; Provencher et al., 2018). Although Woods et al. (2019) have already developed effect factors due to entanglement from macroplastics, research into accounting for these impacts in LCA is ongoing through the MariLCA working group (Marilca, 2020). Finally, inventory flows linked to the presence of nano-, micro- and macroplastics, which can be potentially ingested, remain scarce, although certain initiatives, such as the study by Stefanini et al. (2020), or the PLP report recently published by Quantis (2020).

Similarly, the environmental consequences of the release of plastic debris to water bodies has arisen the interest of the LCA community, since this environmental dimension is not included in current metrics. In fact, Saling et al. (2020) have recently proposed a characterization model regarding the relationship between degradation and fragmentation of plastics in the marine environment. Moreover, Woods et al. (under review), have produced a detailed framework in which they describe the main cause-effect pathways that must be considered in LCIA in order to account for the different damages to human health (mainly through seafood), ecosystem quality (e.g., entanglement or invasive species) (Woods et al., 2019) and other endpoint damages.

3.5.2 Waste valorisation

Another challenge the seafood sector is facing is the issue of seafood waste, which can indirectly increase pressure on fisheries through increased fishing effort to supplement this waste. It is estimated that around 40% of the total food supply is lost or wasted between harvesting, production and processing (Laso et al., 2016; Love et al., 2015). In Europe it estimated that seafood losses and wastage rates are greater than 30% (FAO, 2011). This loss and the knock-on effect of triggering increased fishing effort to meet market demand perpetuates a linear economy of use and waste in food production. The adaptation of a circular economy based on business models which replace the 'end-of-life' concept with reducing, alternative reuse, recycling and recovering materials in production/distribution and consumption processes, at the micro, meso and macro level can promote the minimisation of food loss and wastes through the development of more sustainable production loops (Kirchherr et al., 2017). One of the main avenues in closing the loop in seafood production is through the valorisation of classical waste streams and their utilisation in other industries while eventually being fed back to the original industry (de la Caba et al., 2019). An example of this would be sludge from finfish aquaculture and its use as a substrate for anaerobic digestion and electricity generation. Examples of valorised waste which were mentioned in this review article were: trimmings, such as heads and spines, as fishmeal and fish oil, waste meat or flesh as a paste (Laso et al., 2016) and mussel shells as a source for calcium carbonate (Iribarren et al., 2010a). A circular economy approach applied to these waste streams can highlight management and valorisation opportunities for sectors, processors and companies. Examples of waste or co-product valorisation were previously discussed in Section 3.1.3.

Emerging valorisation strategies include the use of by-products as bio-based materials (García-Santiago et al., 2020). Fish waste has been used for biodiesels and activated carbon production mainly via extractions from fish oil (Fadhil et al., 2017). Blood waters from pelagic processing plants have been shown to be a potential source of proteins, amino acids and vitamins which can be used as ingredients for bio-based materials such as fuels, inks and feeds (Barr and Landis, 2018; Fadhil et al., 2017; Hayes and Gallagher, 2019). A similar approach of extracting glycogen from wastewater has been put forward for mussel processing sites (Barros et al., 2009), where it may be used for lactic acid production. In the instance of fish skin and bone, collagen from these wastes can be valorised as fish gelatine and in the manufacturing of active packaging (de la Caba et al., 2019).

3.5.3 Packaging

A key area in which LCA was applied and valorisation of waste streams can play a role is that of seafood packaging. Several studies reviewed in this article have identified the issue of packaging as being a hotspot in the environmental impact of seafood products. The majority of these studies have focused on canned products, such as European anchovies (Laso et al., 2016, Laso et al., 2017b; Laso et al., 2018), Peruvian anchovies (Avadí and Fréon, 2015; Avadí et al., 2014a), sardines (Almeida et al., 2015; Hospido et al., 2006; Vázquez-Rowe et al., 2014b; Laso et al., 2016) with several studies also considering fresh and frozen products, mussels (Iribarren et al., 2010; Svanes et al., 2011; Thrane, 2006; van Putten et al., 2016). The studies have focused on the use of conventional packaging techniques and materials, but a benchmarking and deeper investigation of these materials from a life cycle perspective including their production, recyclability prospects, or substitution by innovative packaging materials (de la Caba et al., 2019) as well as on the packaging design optimization can help in reducing the environmental challenge associated with this stage of the product life cycle.

3.5.4 Best Available Techniques

Other means of implementing LCA and circular economy philosophies in the seafood sector can be reached through BATs (Barros et al., 2009; Laso et al., 2016; Laso et al., 2017; Morris et al., 2019). A number of studies (Barros et al., 2009; Laso et al., 2017) have demonstrated that BATs and the use of environmental management tools such as maintaining an accurate inventory and promoting recycling of by-products and wastes could reduce the environmental burden on environmental aspects such as energy, water and raw material consumption.

As these processes and valorisation strategies exit the research phase and enter validation and trial stages, it will be important to consider their influence on the life cycle impacts of seafood products. There is an opportunity to implement circular economy and life cycle techniques in the seafood sector, which can help it to become an example of how a transition from a linear to a circular economy may be achieved.

3.5.5 Climate change

Finally, climate change can interact with fisheries in many different ways, through the increase in water temperatures, extreme water flow events (floods and droughts), and warming of maritime environments (Ruiz-Salmón et al., 2020). Regarding the sea surface temperatures (SST), it was found that warming is not homogeneous, and the pattern is complex, as observed in the Atlantic Ocean. Garrett et al. (2018) noted that data were not uniform in 2017 at Malin Head (north of Ireland), and were the highest on record at 0.89°C above the 1981-2010 average. Nevertheless, some areas of the North Atlantic show a slight cooling, such as the subpolar gyre close to 50°N. This location, sometimes referred to as the "cold blob" (Rahmstorf et al., 2015), has cooled by about 0.9 °C since 1900 (Allan and Allan, 2019). In the mid-Atlantic (longitude approx. of Reykjavik and latitude approx. of Liverpool/Galway) seasonal cycle ranges from less than 10°C to almost 15°C (NOAA, 2019). Additionally, in this location a general increase in annual SST has been observed, especially through the last 20 years with 2015 and 2018 being cooler than the long-term average (Rayner et al., 2003).

These changes may impact migration routes of fish, such as mackerel, and stock recovery. Fish migrate between different regions in part based on water temperature through the year as fish species have evolved narrow temperature tolerances (Cheung et al., 2016). This will also adapt their cellular machinery to tolerate a wider range of temperatures, which demands a lot of energy. Fish bodies start to fail when they find themselves in warmer water, so they have to use their energy to move to cooler waters instead of breeding or searching for food. This problem was studied by Pinnegar et al. (2017) for mackerel. The authors set out a series of impacts of climate on UK fisheries, noting the spread of this species into Icelandic and Faroese waters, impacting quota allocation between nations and fleets and governance. Although these aspects are yet to be included in LCA studies, it is possible that the impact of plastic litter working as a vector for invasive species will be included within the Marilca framework (Marilca, 2020).

Moreover, energy use in the capture stage of fishing is large especially when compared to the nutritional energy that is gained. Trawling for small pelagic fish, for instance, result in about 12.5 kg fish per kg of fuel, whereas when trawling for shrimp the fuel to fish ratio is can be between 3 and 4 kg fish per kg of fuel (Furuya et al., 2011; Parker et al., 2018). Despite the improved efficiency of midwater trawling as compared to bottom trawling, however, a wide range of LCA studies demonstrate the better energy performance of pelagic nets, such as purse seines (Driscoll and Tyedmers, 2010; Vázquez-Rowe et al., 2010a; Avadí and Fréon, 2013; González-García et al., 2015). This excludes further energy costs in on shore processing, distribution or storage. In fact, for fisheries, EROI or edible protein EROI have shown to be highly relevant when examining the fishery stage, which as previously explained, is highly energy intensive (Vázquez-Rowe et al., 2014a). EROI considers the energy extracted from the edible content of the fish divided by the energy consumed in the production process (e.g., fuel use in the harvesting stage). Guillen et al. (2016) analysed the EROI of selected European fishing fleets in 2008. They estimated the total EROI average (here presented as a decimal) as being 0.11: the energy content of fuel burnt was 9 times greater than the edible energy content of the catch, with gear-specific EROI values ranging from 0.02 for beam trawl to 1.12 for pelagic trawlers and seiners capturing low value species (e.g. herring, mackerel, sand eels and sprats). In addition, they compared the EROI of fish species to those of other food systems. For instance, the EROI for soybeans was estimated at 4.92, corn 0.81, wheat 0.89, beef (pastured-based) 0.05, and broiler poultry 0.177. Strategies to improve the performance of the fishing industry should include behavioural, technological and managerial efforts since the potential to reduce fuel consumption varies substantially between fisheries (Parker et al., 2018).

4. CONCLUSIONS

LCA has emerged as a powerful methodology for the environmental evaluation of the seafood sector along its supply chain. In fact, the increasing number of studies published demonstrate the interest of researchers, decision makers and stakeholders in the seafood sector to use LCA for the decision-making process. In fact, the seafood sector has used LCA to address many environmental sustainability challenges and, in turn, the studies carried out by LCA practitioners have served to reinforce LCA as a valid tool to deal with sustainability challenges for seafood and other sectors. Both parties need to continue this path together in order to increasingly sustain the level of innovation necessary for the sector to grow in the current context. The common challenge is to continue enriching each other and move forward in attaining improved sustainability in the sector. To this end, there are a number of key areas to be addressed.

The main methodological challenges for the LCA tool applied to the seafood sector lie in: (i) identifying and defining the reference system so that different studies are more comparable and harmonized; (ii) establishing consensual rules for defining system boundaries, and (ii) clearly defining not only the functional unit, but also the function of the system. In terms of Life Cycle Inventory, the availability of inventory flows for nations and fisheries in the developing world are still substantially lower than for the developed world, especially Europe, where most seafood LCA studies have been conducted. In fact, most studies linked to developing countries have covered the extraction of fish resources that are ultimately exported to developed markets. Moreover, while certain databases have provided an upgrade of their inventory flows in recent years, some if which include fisheries and seafood products (e.g., Ecoinvent), there is still a lag between seafood-based products and other food commodities. From an LCIA perspective, the main challenges are linked to providing a more complete scope of environmental impacts and damages related to the marine environment. While other methodological challenges remain when assessing the impact of ocean-related activities, including fisheries, the addition of impact categories linked to plastic debris in the ocean and fisheries depletion would potentially enhance the utility and visibility of LCA within fisheries management authorities and scientists.

The main outlook of this review is that a life cycle approach is essential for understanding the nexus along the whole supply chains. The water–energy–food nexus approach appears to be crucial to monitoring of the SDGs, since it considers intersectoral synergies and complementarities that will be crucial to improve the sustainability of the fish and seafood processing sector within the CE framework and according to the 2030 EU agenda. Recommended future work should, therefore, include the development of guidelines adapted to the seafood sector, as well as additional empirical case studies that quantify in addition to the environmental impacts, social and economic impacts caused by the new challenges of the circular economy and the bio-economy. For the former, the release of the PEFCR for the fishing sector, which is expected in upcoming years, may shed light on a more harmonized way of conducting LCA studies for the sector. The development of nexus guidelines for the sector would also allow an enhanced interconnection of seafood LCA with other pillars of sustainability. For the latter, further integration of LCA with a wide array of economic, social, nutritional methods, or its integration with machine learning models may enhance the utility of the tool in the future. In this sense, we argue that although LCA must continue to expand its holistic perspective by updating and upgrading its inventory databases and impact assessment methods, it cannot cover the entire set of sustainability indicators, especially beyond those that are purely environmental, that fisheries managers seek to respond. Consequently, beyond a PEFCR for the sector, higher levels of harmonization between LCA and other management support tools must be undertaken to foster the utility of life cycle methodologies in the sector. The aforementioned may be also informed by carrying out risk assessment modelling, which together with LCA, will help future proof the seafood sector for sustainable development along with mitigating against uncertainties.

Accurate assessment by means of LCA based tools represents an excellent opportunity to contribute to the economic, social and environmental development of the seafood sector, but also implies a high responsibility that needs to be articulated through tangible mid and long-term actions. LCA can jointly address a global concern and interest in terms of policies and strategies aimed at climate change mitigation, energy and food security, marine debris or treatment of wastewater. To address the challenges posed by these objectives, sustainable and multilateral research cooperation is needed to define integrated methodologies and strategies, such as the water-energy-food nexus, a valuable tool to minimize environmental negativities and get successful synergies. Furthermore, the added methodological challenge is to integrate environmental, social and economic variables that meet national needs through transnational strategies. The establishment of synergies in knowledge and experiences and challenges at the local level will help overcome challenges at a global level.

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Table 1. Main characteristics of the reviewed LCA studies: Functional Unit, System Boundaries, Allocations and Sensitivity analysis.

Reference	Targeted species	Functional unit	System boundaries	Allocation method	Sensitivity analysis
Abdou et al., 2018	Shrimp and demersal finfish (*Sparidae Diplodus annularis, Sparus aurata*), mullets (*Mullus barbatus, M. surmuletus*), rays (e.g. *Raja clavata*) and sharks (e.g. *Mustelus mustelus*).	1 t of landed seafood	Cradle to gate	No	No
Abdou et al., 2020	Shrimp and demersal finfish (*SparidaeDiplodus annularis, Sparus aurata*), mullets (*Mullus barbatus, M. surmuletus*), rays (e.g. *Raja clavata*) and sharks (e.g. *Mustelus mustelus*).	1 t of landed seafood	Cradle to gate	No	Yes, management scenarios: establishment of marine protected areas, extension of the biological rest period, and decrease in the number of demersal trawlers.
Almeida et al., 2014	European pilchard (*Sardina pilchardus*)	1 kg of landed sardine,	Cradle to gate	Mass	Yes, gear and time lapse comparison.
Almeida et al., 2015	European pilchard (*Sardina pilchardus*)	1 kg edible of canned sardine with olive oil	Cradle to gate	Mass	Yes, packaging analysis and comparison with other seafood products.
Avadí et al., 2014a	Peruvian anchoveta *(Engraulis ringens)*	1 kg of fish in the final product	Cradle to gate	Mass	Yes, electricity reduction, packaging material and reduction in-plant discards.
Avadí et al., 2014b	Peruvian anchoveta *(Engraulis ringens)*	1 t of landed fish	Cradle to gate	No	Yes, Data Envelopment Analysis (DEA) to

					determine the relative efficiencies of multiple comparable units.
Avadí et al., 2015	Ecuadorian tuna yellowfin *(Thunnus albacares)*, skipjack *(Katsuwonus pelamis)* and bigeye *(Thunnus obesus)*	1 t of tuna product	Cradle to gate	Mass	Yes, fuel use intensity and packaging material.
Avadí and Fréon, 2015	Peruvian anchoveta *(Engraulis ringens),* trout *(Oncorhynchus mykiss)*, tilapia *(Oreochromis spp.)* and black pacu *(Colossoma macropomum)*	1 t of edible fish in a Direct Human Consumption product in the case of anchoveta and fresh fish edible portion for cultured species.	Cradle to gate	Mass	No
Avadí et al., 2018	Peruvian hake (*Merluccius gayi peruanus*)	1 t of whole hake landed	Cradle to gate	Mass	Yes, fuel use intensity and comparison with published results from other hake fisheries and with another Merlucciidae fish, the Patagonian grenadier (*Macruronus magellanicus*).
Avadí et al., 2019	South Pacific anchovies and hake (including *Patagonian grenadier-Macruronus magellanicus*) and Pacific tunas (*Thunnus spp.*), tilapia (*Oreochromis spp.*) and trout (*Oncorhynchus*	N/A	Cradle to grave	Mass, economic	No

	mykiss)				
Denham et al., 2016	Different species of finfish: Crimson snapper (*Lutjanus erythropterus*), Bluespotted emperor (*Lethrinus punctulatus*) and Rosy threadfin bream (*Nemipterus furcosus*) among others.	1 t of processed fish sold at retail	Gate to gate	Mass	Yes, cleaner production strategies: solar electricity, biogas electricity, reduction of GHG emissions from refrigeration, and utilizing waste to develop by-products.
Driscoll and Tyedmers, 2010	Atlantic herring (*Clupea harengus*)	1 t of fish landed	Cradle to gate	N/A	Yes, variations of Total Allowable Catch and purse seine fishing effort.
Driscoll et al., 2015	American lobster (*Homarus americanus*)	1 t of live lobster	Cradle to gate	Mass	Yes, comparison of different scenarios: no allocation between the main product and co-products, electricity use for storage, fuel use in vessel, different database for fuel combustion and post-capture mortality rate.
Farmery et al., 2015	White banana prawn (*Fenneropenaeus merguiensis*)	1 kg of frozen prawn	Cradle to gate	Mass	Yes, comparison of impact method (IPCC 100 years, CML 2 Baseline 2000 and ReCiPe). Also catch variation: 10% increase and decrease in catch with the same

					number of boat days.
Fréon et al., 2010	Peruvian anchoveta (*Engraulis ringens*)	100 g of protein	Cradle to gate	No	No
Fréon et al., 2014b	Peruvian anchoveta (*Engraulis ringens*)	1 t of fresh fish	Cradle to gate	No	No
Fréon et al., 2014c	Peruvian anchoveta (*Engraulis ringens*)	1 t of fresh fish	Cradle to gate	Mass and economic	Yes, simulations of fuel use variations of ±20% and recomputing single scores considering mass allocation.
Fréon et al., 2017	Peruvian anchoveta (*Engraulis ringens*)	(i) 1 t of fish oil or fishmeal at the gate of the plant and (ii) 1 t of raw material at the plant	(i) Cradle to gate and (ii) Gate to gate	Gross energy content, economic value and mass	Yes, cleaner production strategies: using natural gas instead of heavy fuel.
González-García et al., 2015	European pilchard (*Sardina pilchardus*)	1 t of landed pilchard	Cradle to gate	No	No
Hallstrom et al., 2019	Alaskan pollock (*Theragra chalcogramma*), Arctic char (*Salvelinus alpinus*), Cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), Atlantic salmon (*Salmo salar*), Cape hake (Merluccius capensis), Cephalopods (*Cephalopoda spp.*),	N/A. Results of GHG emissions and nutritional score are presented as a variation of the median of the entire analysed sample.	Cradle to gate	No	Yes, variation in nutritional results when using different methods.

	European eel (*Anguilla anguilla*), European flounder (*Platichtys flesus*), Hake (*Merluccius merluccius*), Seabass (*Dicentrarchus labrax*), Sprat (*Sprattus sprattus*), Gilt-head seabream (*Sparus aurata*), Haddock (*Melanogrammus aeglefinus*), Hoki (*Macruronus novaezelandiae*), Lobster (*Homarus gammarus*), Northern prawn (*Pandalus borealis*), Norway lobster (*Nephrops norvegicus*), Oyster (*Ostreidae spp.*), Pangasius (*Pangasius hypophthalmus*), Perch (*Perca fluviatilis*), Pike (*Esox lucius*), Pike-perch (*Sander lucioperca*), Pink salmon (*Oncorhynchus gorbuscha*), Plaice (*Pleuronectes platessa*), Rainbow trout (*Oncorhynchus mykiss*), Saithe (*Pollachius virens*), Scallop (*Pecten maximus*), Tilapia				

	(*Oreochromis niloticus*), Trout (*Salmo trutta*), Turbot (*Scophthalmus maxima*), Whitefish (*Coregonus spp.*), Whiting (*Merlangius merlangus*)				
Hélias et al., 2018	Black-bellied anglerfish (*Lophius budegassa*), White anglerfish (*Lophius piscatorius*), Cod (*Gadus morhua*), Roundnose grenadier (*Coryphaenoides rupestris*), Haddock (*Melanogrammus aeglefinus*), Hake (*Merluccius merluccius*), Greenland halibut (*Reinhardtius hippoglossoides*), Herring (*Clupea harengus*), Ling (*Molva molva*), Blue ling (*Molva dypterygia*), Mackerel (*Scomber scombrus*), Horse mackerel (*Trachurus trachurus*), Megrim (*Lepidorhombus whiffiagonis*), Four-spot megrim (*Lepidorhombus boscii*), Plaice (*Pleuronectes platessa*), Beaked redfish	N/A	N/A	No	No

	(*Sebastes mentella*), Golden redfish (*Sebastes norvegicus*), Saithe (*Pollachius virens*), Sandeel (*Ammodytes spp.*), Seabass (*Dicentrarchus labrax*), Sole (*Solea solea*), Sprat (*Sprattus sprattus*), Tusk (*Brosme brosme*), Whiting (*Merlangius merlangus*) and Blue whiting (*Micromesistius poutassou*)				
Hospido and Tyedmers, 2005	Skipjack tuna (Katsuwonus pelamis) and Yellowfin tuna (*Thunnus albacares*)	1 t of frozen fish landed	Cradle to gate	No, they consider various target species within their global FU	Yes, increase and decrease fuel inputs by one standard deviation and the use of alternative emission factors from different sources.
Hospido et al., 2006	Tuna (*Thunnus albacares*)	1 t of frozen fish entering the factory	Gate to grave	Economic (for transport from retailers to households)	Yes, improvement actions: recycled percentage of packaging materials, substitution of packaging materials.
Iribarren et al., 2010a[1]	Mussel (*Mytilus galloprovincialis)*	(i) 1 kg of fresh mussels and (ii) 1 kg of canned mussels' flesh	Purification/transformation and consumption stages. Excluded mussel culture and valorization of mussel organic waste and shells	Mass	No
Iribarren et al., 2010b[1]	Mussel (*Mytilus galloprovincialis):*	(i) 100 t of mussel shells and (ii) 100 t of mussel organic	Grave to grave: valorization of shells to calcium carbonate and organic waste to fish meal	System expansion for waste valorization	Yes, differences between current methodology of

		remains			valorization (producing calcium carbonate) and others (landfilling, incineration) are considered. Also, similar differences between current organic waste valorization to fish meal and alternative production of mussel pate are analyzed.
Iribarren et al., 2010c[1]	Mussel (*Mytilus galloprovincialis)*	100 kg of cultured mussel: 40 kg for fresh, 35 canning, 20 frozen in cooking-freezing plants and 5 from cooking plants for cannery. For comparative effects 1 kg of fresh, canned or frozen mussel	Cradle to grave named business-to-consumer (B2C)	System expansion for waste valorization (same procedure that Iribarren et al 2010b)	Yes, regarding analysis based on 1 kg of protein supplied comparing mussels and chicken and canned tuna.
Iribarren et al., 2010d[1]	Mussel (*Mytilus galloprovincialis)*	One triple pack or rounds cans format (129 g of canned mussels, 120 g of sauce, 81 g of primary packaging and 12.73 g of	Cradle to grave (B2C)	System expansion for waste valorization (same procedure that Iribarren et al 2010b)	No

		secondary packaging)			
Iribarren et al., 2010e	Species from coastal fishing (horse mackerel, Atlantic mackerel, European pilchard and blue whiting), offshore fishing (european hake, megrim and anglerfish), deep-sea fishing (skipjack and yellowfin tuna), extensive aquaculture (mussels) and intensive aquaculture (turbot)	1 t of fish	Cradle to gate	Economic and mass (sensitivity analysis)	Capital goods are relevant in carbon footprint results for extensive aquaculture species but not for the others.
Iribarren et al., 2011	Species from coastal fishing, offshore fishing, deep-sea fishing, extensive aquaculture and intensive aquaculture (same species that Iribarren et al 2010e)	1 t of fish	Cradle to gate	Economic and mass	Yes, based on the type of cooling agents.
Laso et al., 2016	Anchovy *(Engraulis encrasicolus)*	For heads and spines: 1 t of fish meat entering the plant. For the remaining and broken fish: 1 t paste processing	Gate to grave.	Economic and system expansion for anchovy waste valorisation	No
Laso et al., 2017a	Anchovy *(Engraulis encrasicolus)*	1 can of fish in extra virgin olive oil.	Cradle to gate (from fish to factory), gate to gate (factory process and canned products) and gate to grave (distribution and use and EoL)	System expansion for anchovy waste valorisation	Yes, different scenarios: packaging recycling is proposed - Application of BATs for canned

					anchovy industry such as recycle process water, recycle cardboard boxes, separate possible valorization streams, dry cleaning…
Laso et al., 2017b	Anchovy *(Engraulis encrasicolus)*	1 kg of fish entering the canning plant	Cradle to grave	System expansion, mass and economic	Yes, sensitive analysis based on mass or economic allocation.
Laso et al., 2018a	Anchovy *(Engraulis encrasicolus)*	1 kg of processed fish	Cradle to grave	System expansion	Yes, Green protein footprint according the packaging type or no packaging.
Laso et al., 2018b	Anchovy *(Engraulis encrasicolus)*	1 kg of fish	Cradle to gate	System expansion	No
Laso et al., 2018c	Anchovy *(Engraulis encrasicolus)*	1 t fish food loss (FL)	2 scenarios: Food waste-to-energy-to-food" and "Food-waste-to-food".	System expansion	No
Lourguioui et al., 2017	Mussel *(Mytilus galloprovincialis)*	1 t of mussels	Cradle to gate	No	Scenarios for mussel farms management and uncertainty analysis/Monte Carlo
Lozano et al.,2010	Mussel	1 t of mussels for each raft	Cradle to gate	No	No
Parker and Tyedmers, 2012a	Antarctic krill (*Euphausia superba*)	1 kg of krill meal 1 L of krill oil 1 consumer-ready bottle of 60 omega-3 krill oil capsules	(i) Krill meal and oil: cradle to consumer (ii) Krill omega-3 capsules: cradle to retailer	(i) Krill meal and oil: energy content in fishing and primary processing (ii) Krill meal and oil: mass in transport	Application of three allocation scenarios to omega-3 capsules. Scenario analyses of different parameters for krill meal and omega-3 capsules.

				to port (iii) Krill omega-3 capsules: system expansion in the secondary processing	
Parker and Tyedmers, 2012b	Peruvian anchovy *(Engraulis ringens)*, Atlantic herring *(Clupea harengus)*, Gulf menhaden *(Brevoortia patronus)*, blue *whiting (Micromesistius poutassou)* and Antarctic krill *(Euphausia superba)*	For each species: 100 GJ of combined meal and oil products, respecting the species-specific yields of meal and oil	N/A	Output nutritional energy of meal and oil products	Uncertainty analysis/Monte Carlo Sensitivity analysis to the FU (basis of comparison between species): ▪ 100 GJ of energy from meal and oil (baseline); ▪ 1 t of protein from meal and oil ▪ 1 t wet weight biomass
Parker et al., 2014	4 tuna species: skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacores*), albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*)	1 t of landed fish	Cradle to gate	Mass	No
Ramos et al., 2011	North East Atlantic Mackerel (NEAM) *(Scomber scombrus)*	1 t of landed round fish	Cradle to gate	Temporal allocation	No
Svanes et al., 2011	Cod *(Gadus morhua)*	1 kg cod wetpack, frozen, in 400 g packages, delivered to retailer	Cod wetpack and cod burger: cradle to consumer Processed cod loin: cradle to distribution Cradle to gate (arrival at the processing	Mass and economic	Sensitivity analysis based on either mass and economic allocation.

		in Sweden 1 kg cod burger, frozen, in 5 kg packages, delivered to institutional buyer in Sweden 1 kg processed cod loin product in 2 kg package, delivered to distribution centre in the UK 1 kg processing residue, frozen, going to animal feed production in Norway	plant)		Scenario analyses on different parameters.
Van Putten et al., 2015	Tropical rock lobster (TRL, *Panulirus ornatus*) and southern rock lobster (SRL, *Jasus edwardsii*)	1 kg of lobster	Cradle to consumer	a) mass, assuming heads are wasted; b) mass, assuming heads are used; c) nutritional value (total MJ of edible product); d) economic (ex-vessel price)	Scenario analyses, using base case mass allocation on different parameters.
Thrane, 2004	Codfish, flatfish, prawn, shrimp, Norway lobster, mussels, herring, mackerel, industrial fish	1 kg of fish	Cradle to gate	System expansion and mass and economic allocation	No

Thrane, 2006	Flatfish	1 kg of frozen fish filet	Cradle to cradle	System expansion and mass and economic allocation	No
Vázquez-Rowe et al., 2010a	Atlantic horse mackerel (*Trachurus trachurus*)	1 t of round fish	Cradle to gate	Mass and economic	Yes
Vázquez-Rowe et al., 2010b	European hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), Atlantic mackerel (*Scomber scombrus*), blue whiting (*Micromesistius potassou*)	1 kg of fish	Cradle to gate	No, global catch value was considered as FU	No
Vázquez-Rowe et al., 2011a	European hake (*Merluccius merluccius*)	500 g of gutted fish fillet	Cradle to grave	Mass and economic	No
Vázquez-Rowe et al., 2011b	Broad number of vessels within selected Galician fishing fleets (target species are quite varied, depending on the gear type and geographical zone where they fish)	1 t of landed fish	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2012a	Common octopus (*Octopus vulgaris*)	24 kg of frozen octopus up to the point of import	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2013a	Hake (*Macruronus magellanicus*) fish sticks produced in a processing plant in Spain	1 package of 10 frozen fish sticks	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2013b	Hake (*Macruronus magellanicus*) fish sticks produced in a processing plant in Spain	1 package of 10 frozen fish sticks	Gate to grave	Mass	No
Vázquez-	Goose	1 kg of	Cradle to gate	No, due	No

Rowe et al., 2013c	barnacle (*Pollicipes pollicipes*)	barnacles		to the lack of co-products	
Vázquez-Rowe et al. 2014a	Seafood species landed in Galician ports	1 of fish	Cradle to gate	Mass	No
Vázquez-Rowe et al., 2014b	European pilchard (*Sardina pilchardus*)	Amount of protein (17.26 g) supplied by one can of sardines (85.0 g) in olive oil	Cradle to gate	Mass, economic and energy	No
Villanueva-Rey et al., 2018	European pilchard (Sardina pilchardus)	1 t of fish	Cradle to gate	Mass	Yes, different assessment methods, allocation approach (economic), fishing gear life span, base port influence, engine type.
Winther et al., 2009	Norwegian seafood supply chain: a) aquaculture: Atlantic salmon (*Salmo salar*) and Blue mussels (*Mytilus edulis*); b) fishing: cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), herring (*Clupea harengus*) mackerel (*Scomber scombrus*)	1 kg of edible product	Cradle to gate	Mass	Yes, different scenarios were analyzed: electricity mix, product waste, edible yield, allocation approach (economic), utilization of processing stage by-products, feed conversion ratio, refrigerant agent, etc.
Ziegler et al., 2003	Cod (*Gadus morhua*)	400 g of fish fillets	Cradle to gate	Economic	Yes, different scenarios were considered for fishing based on fishing gear.
Ziegler and	Norway lobster	300 g of	Cradle to gate	Economic	Yes, fuel use,

Valentinsson, 2008	(*Nephrops norvegicus*)	lobster tails			allocation choice, product yield, impact assessment method and background data.
Ziegler et al., 2011	Southern pink shrimp (*Penaeus notialis*)	1 kg of shrimp	Cradle to gate	Economic	No

[1] The production of mussels *(Mytilus galloprovincialis*) in Galicia, Spain, corresponds to extensive aquaculture. However, an important auxiliary fishing fleet (1267 vessels according to the 2020 regional census) supports the cultivation of mussels in mussel rafts along the Galician rias (Pesca de Galicia, 2020).

Table 2. Frequency of LCIA impact categories and methods application in the reviewed studies

Impact categories	CML-IA	ReCiPe	ESA IChemE	Others methods/ indicators	N studies	%
Climate change	GWP	CC	GWP	-	54	86%
Ozone depletion	ODP	OD	SOD	-	31	49%
Photochemical oxidant formation	POFP	POF	POF	-	25	40%
Particulate matter formation	-	PMF	-	-	8	13%
Ionizing radiation	-	IR	-	-	6	10%
Acidification	AP	TA	AA	-	38	60%
Eutrophication	EP	FE, ME	E, AOD	-	39	62%
Ecotoxicity	METP, TETP	TE, FE, MET	EAL, EAL2	-	27	43%
Human toxicity	HTP	HT	-	-	19	30%
Land use	LOP	ALO, ULO, NLT	-	-	13	21%
Abiotic depletion	ADP	MD, FD	-	-	24	38%
Water use	-	WD	-		10	16%
Energy demand	-	-	-	CED, TCED, EU	27	43%
Biotic (fish) resources use	-	-	-	see detailed analysis	22	37%
Nutritional impact	-	-	-	see detailed analysis	7	12%
Sea-bed damage	-	-	-	see detailed analysis	1	2%
Socio-economic	-	-	-	see detailed analysis	3	5%

GWP: Global Warming Potential; CC: Climate Change; ODP: Ozone Depletion Potential; OD: Ozone Depletion; SOD: Stratospheric Ozone Depletion; POFP: Photochemical Oxidant Formation Potential; POF: Photochemical Oxidant formation; PMF: Particulate matter formation; IR: Ionizing radiation; AP: Acidification Potential; TA: Terrestrial acidification; AA: Atmospheric acidification; EP: Eutrophication Potential; FE: Freshwater eutrophication; ME: Marine eutrophication; E: Eutrophication; AOD: Aquatic oxygen demand; METP: Marine Eco-Toxicity Potential; TETP: Terrestrial Eco-Toxicity Potential; TE: Terrestrial ecotoxicity; FE: Freshwater ecotoxicity; MET: Marine ecotoxicity; EAL: Ecotoxicity to aquatic life (metals to seawater); EAL2: Ecotoxicity to aquatic life (other substances); HTP: Human Toxicity Potential; HT: Human toxicity; LOP: Land Occupation Potential; ALO: Agricultural land occupation; ULO: Urban land occupation; NLT: Natural land transformation; ADP: Abiotic Depletion Potential; MD: Metal depletion; FD: Fossil depletion; WD: Water depletion; CED: Cumulative energy demand; TCED: Total Cumulative Energy Demand; EU: Energy use.

Table 3. Impact categories per study.

Study	LCIA Method	Typical LCIA indicators												LCI	Fishery specific			
		Climate change	**Ozone depletion**	**Photochemical oxidant formation**	**Particlaute matter formation**	**Ionizing radiation**	**Acidification**	**Eutrophication**	**Ecotoxicity**	**Human toxicity**	**Land use**	**Abiotic depletion**	**Water use**	**Energyu demand**	Biotic (fish) resources use	Sea use	Nutritional	Socio-economic
Abdou et al., 2018	CML baseline 2000	X	X	X			X	X	X	X	X	X		X	X	X		
Abdou et al., 2020	Ecopath with Ecosim (EWE)	X	X	X			X	X	X	X	X	X		X	X			
Almeida et al., 2014	CML baseline 2 2002	X	X				X	X						X	X			
Almeida et al., 2015	CML-IA baseline	X	X	X			X	X	X			X		X				
Avadí et al., 2014a	ReCIPE, CML baseline 2000 and USEtox	X					X	X		X	X	X	X	X	X			
Avadí et al., 2014b	ReCIPE	X	X	X	X	X	X	X	X	X	X	X	X					
Avadí et al., 2015	ReCiPe	X		X	X			X		X		X		X				
Avadí and Fréon, 2015	ReCIPE, CML-IA baseline 2000 and USEtox	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X
Avadí et al., 2018	ReCiPe	X		X	X			X	X	X	X	X	X	X	X			
Denham et al. 2016	GHGs emission factors	X																
Driscoll and Tyedmers, 2010	GHGs emission factors	X													X			
Driscoll et al., 2015	CML baseline 2 2000	X	X				X					X		X	X			
Farmery et al., 2015	Australian impact method	X						X	X				X	X	X			
Fréon et al., 2010	N/A																	X
Fréon et al., 2014b	ReCiPe, USETox, CML 2000 and 2001	X	X	X	X	X	X	X	X	X	X	X	X					
Fréon et al., 2014c	ReCiPe	X					X	X						X	X			X
Fréon et al. 2017	ReCiPe	X	X	X	X	X	X	X	X	X	X	X	X					
González-García, 2015	ReCiPe	X																
Hallstrom et al., 2019	GHGs emission factors	X																
Hélias et al., 2018	N/A														X			
Hospido and Tyedmers, 2005	CML baseline	X	X	X			X		X	X								
Hospido et al., 2006	CML baseline	X	X	X			X	X				X						
Iribarren et al., 2010a	CML 2000	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010b	CML 2001	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010c	CML 2001	X	X	X			X	X	X	X	X	X						
Iribarren et al., 2010d	PAS 2050 and IPCC, 2007.	X																
Iribarren et al., 2010e	PAS 2050 and IPCC, 2007.	X																
Iribarren et al., 2011	PAS 2050 and IPCC, 2007.	X																
Laso et al., 2016	ESA with metrics from IChemE 2002.	X	X				X	X	X									

Laso et al., 2017a	ESA with metrics from IChemE 2002.	X	X				X	X	X									
Laso et al., 2017b	ESA with metrics from IChemE 2002.	X	X				X	X	X									
Laso et al., 2018a	JRC of EC. IPCC, 2013, ReCiPe, CML-IA	X					X	X										
Laso et al., 2018b	JRC of EC. ReCiPe, CML-IA	X					X	X										
Laso et al., 2018c	IPCC, 2013 and specific calculations	X											X	X			X	
Lourguioui et al., 2017	CML baseline 2000	X					X	X						X				
Lozano et al., 2010	CML baseline 2000	X	X	X			X	X	X	X		X			X			
Parker and Tyedmers, 2012a	CML 2 baseline 2000	X	X				X	X						X	X			
Parker and Tyedmers, 2012b	Marine footprint														X			
Parker et al., 2014	IPCC 2007 characterization factors	X												X	X			
Ramos et al., 2011	CML baseline 2000	X	X				X	X	X			X						
Van Putten et al., 2016	CML baseline 2000	X	X				X	X						X				
Svanes et al., 2011	CML 2 baseline 2000	X	X	X			X	X						X				
Thrane, 2004	ISO 14040-43													X	X	X		
Thrane, 2006	Danish EDIP 97	X	X	X			X	X	X	X				X				
Vázquez-Rowe et al., 2010a	CML baseline 2000	X	X	X			X	X	X	X		X						
Vázquez-Rowe et al., 2010b	CML baseline 2000	X	X	X			X	X				X						
Vázquez-Rowe et al., 2011a	CML baseline 2000	X	X				X	X	X			X			X			
Vázquez-Rowe et al., 2011b	EMEP Corinair, CML baseline 2000	X					X	X	X			X		X				
Vázquez-Rowe et al. 2012a	CML baseline 2000	X	X	X			X	X	X			X			X	X		
Vázquez-Rowe et al. 2013a	IPCC 2001	X												X				
Vázquez-Rowe et al. 2013b	IPCC 2001	X																
Vázquez-Rowe et al. 2013c	IPCC 2001	X												X				
Vázquez-Rowe et al. 2014a	Cumulative Energy Demand													X				
Vázquez-Rowe et al. 2014b	ReCiPe	X	X	X	X	X	X	X	X	X	X	X	X		X	X		
Villanueva-Rey, 2018	ILCD, ReCiPe, CED	X	X	X	X	X	X	X	X	X	X	X	X	X				
Winther et al., 2009	IPCC 2007; CED	X												X				
Ziegler et al., 2003	CML baseline 2001	X		X			X	X						X	X	X		
Ziegler and Valentinsson, 2008	CML baseline 2001, Ecoindicator 99	X	X	X			X	X	X						X	X		
Ziegler et al., 2011	CML baseline 2 2000	X	X	X			X	X	X	X				X	X	X		
	Number of studies	54	31	25	8	6	38	39	27	19	13	24	10	27	22	7	1	3
	%	92%	53%	42%	14%	10%	64%	66%	46%	32%	22%	41%	17%	46%	37%	12%	2%	5%

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- The review dissects 59 LCA studies about seafood, 90% of them over the last decade.
- LCA methodologies, the origin of the research centres and fish species are reviewed.
- LCA is key to climate change mitigation, energy and food sustainability and security.
- Challenges and potential opportunities for the seafood sector are addressed.
- Nexus water-energy-food to reduce environmental impact getting positive synergies.

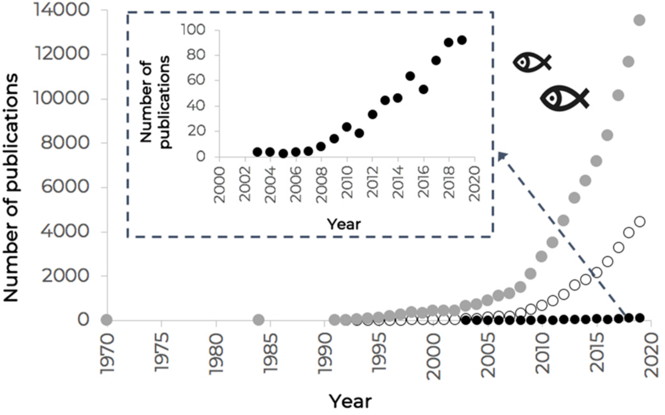

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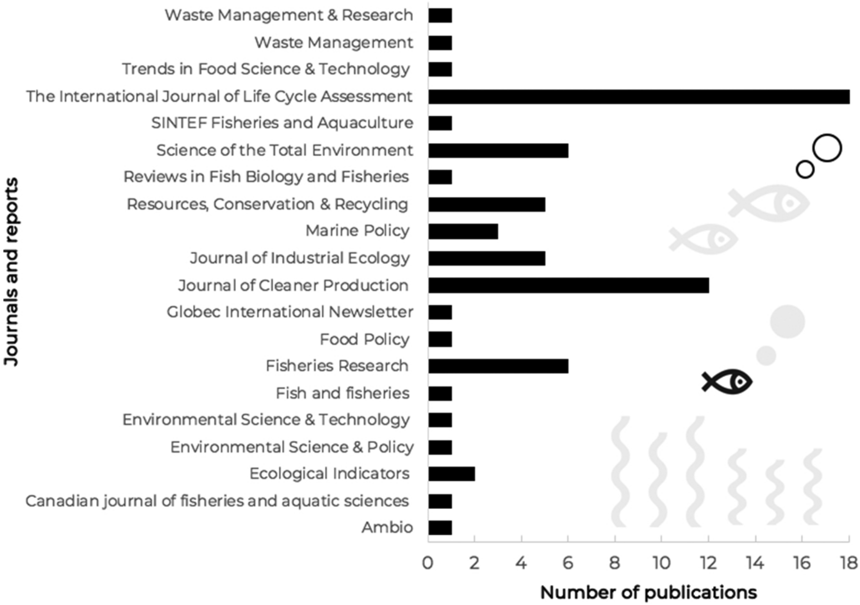
Figure 1


Waste Management & Research
Waste Management
Trends in Food Science & Technology
The International Journal of Life Cycle Assessment
SINTEF Fisheries and Aquaculture
Science of the Total Environment
Reviews in Fish Biology and Fisheries
Resources, Conservation & Recycling
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Environmental Science & Technology
Environmental Science & Policy
Ecological Indicators
Canadian journal of fisheries and aquatic sciences
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Figure 2

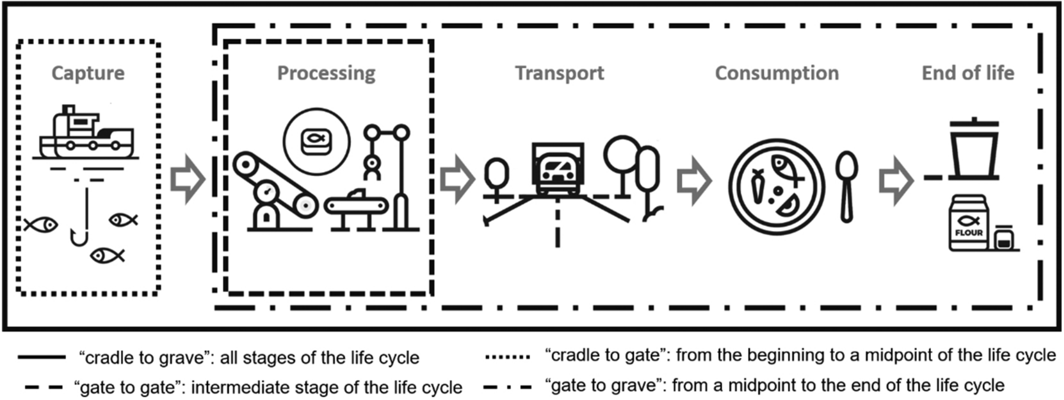
Capture
Processing
Transport
Consumption
End of life
FLOUR
"cradle to grave": all stages of the life cycle
"cradle to gate": from the beginning to a midpoint of the life cycle
"gate to gate": intermediate stage of the life cycle
"gate to grave": from a midpoint to the end of the life cycle

Figure 3

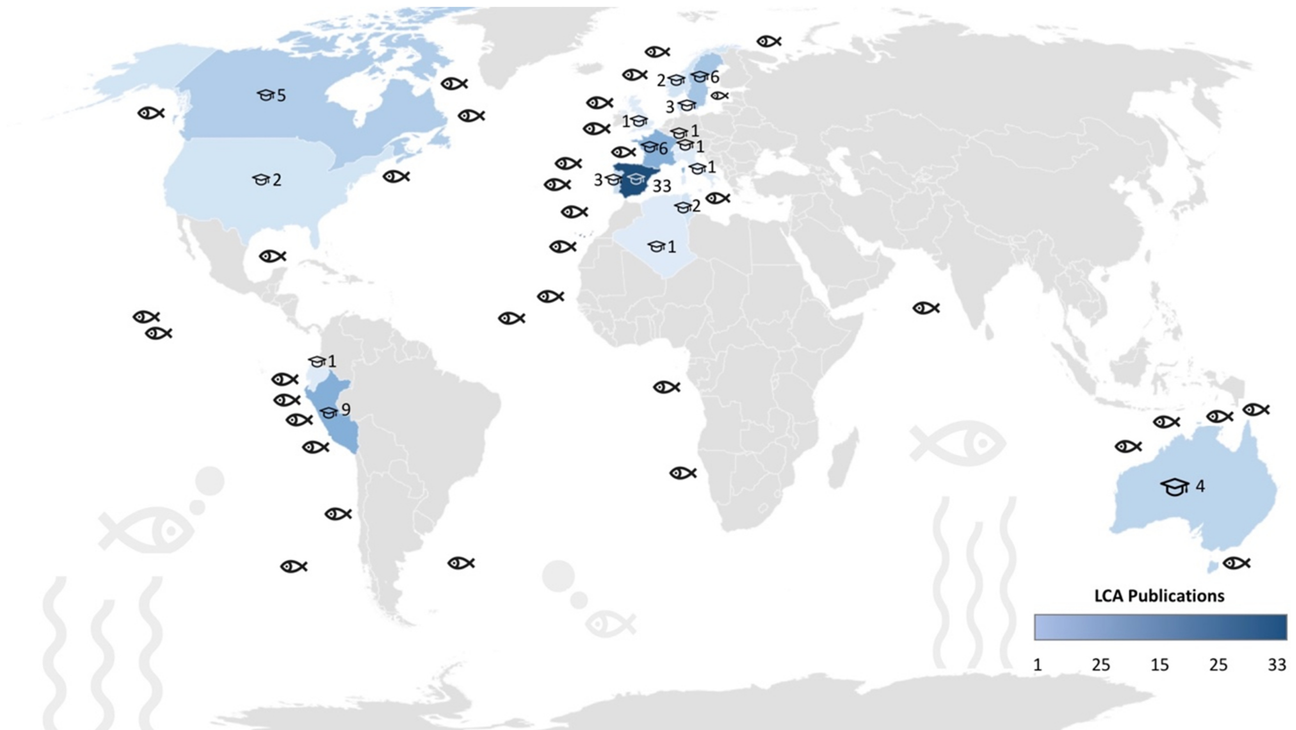

Figure 4