Methodological guidelines for the calculation of a Water-Energy-Food nexus index for seafood products

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1. Introduction

The "ecological footprint" aims to quantify the impacts on environment associated with human activities (Moffatt, 2000). Since the development of this concept several footprints have emerged, being most of them based on the Life Cycle Assessment (LCA) (Hauschild et al., 2018). The latter consists in the analysis of the environmental aspects related to a product or service throughout their different life cycle stages: raw materials extraction, manufacturing, logistics, use and end-of-life (EoL) treatment (ISO, 2016). Moreover, footprints can be applied in a wide variety of contexts: from agri-food systems (Notarnicola et al., 2017) to cities (Rama et al., 2021). According to Hauschild et al. (2018), their main strengths rely on being: (i) suitable for transferring information to non-environmental experts, (ii) accessible and intuitive, and (iii) relatively easy to perform when few data are available. Footprints can also increase environmental awareness, constituting a link between life cycle thinking and policy makers (Ghita et al., 2018), but the focus on a single environmental problem is one of their main drawbacks.

Concerning LCA literature focusing on the seafood sector (i.e., fisheries, aquaculture and processing), these have experienced a proliferation over the last two decades. Despite this, there are currently certain discrepancies in the way they are approached, such as in the definition of the system under study, its boundaries or function. Moreover, the impacts categories considered are often evaluated individually, without carrying out a global analysis that highlights their interconnections so as to achieve more robust and representative results (Ruiz-Salmón et al., 2021). However, the first steps are already being taken towards the construction of a common Life Cycle Inventory (LCI) with the objective of having a common framework (Avadí et al., 2020).

Consequently, on the one hand, the assessment of environmental impacts of seafood production as independent indicators may lead to limited interpretations, although a combination of them taking into account their synergies is of interest with the objective of broadening the scope of the study. On the other hand, the consideration of following a holistic view to integrate the positive contributions of these foods in nutritional terms to their environmental burdens remains largely unexplored. For example, in the case of fisheries, many decarbonization policies are focused on quantifying the greenhouse gas (GHG) emissions. However, other positive contributions related to fish consumption are often overlooked, such as its low proportion of GHG emitted per kg of protein provided, are often overlooked (Entrena-Barbero et al., 2022).

It is from the above rational that the "Water-Energy-Food (WEF) nexus" concept emerged with the aim of promoting the inseparable links between the use of resources to provide the basic and universal rights of food provision, water supply and energy security (Biggs et al., 2015). Associated with the nexus approach is the idea of not prioritizing any specific resource, but rather recognizing the synergies and trade-offs in resource management (Proctor et al., 2021). In addition, in recent years, the food sector has become an object of study to improve its current situation because of the multiple obstacles it has to deal with, such as food waste (Kibler et al., 2018), high levels of pollution (Parker et al., 2018) or food shortages in the supply chain (Singh et al., 2021). In relation to the latter, seafood can be crucial with the aim of tackling malnutrition due to its high nutritional value (Golden et al., 2021). However, fisheries face as well a number of sustainability challenges related to the recovery of fishing stocks (Worm et al., 2009), financial stability of fishermen (Holland et al., 2020), as well as the consequences of climate change (Plagányi, 2019).

In this regard, the European Union opted for the promotion of sustainable production as a strategy for the development of the fisheries sector, improving the use of marine resources, while increasing the economic and environmental aspects for regions with productive sectors associated with the sea of notable importance, the so-called "blue growth" (European Commission, 2017). Furthermore, this strategy has already been applied to control the fisheries management plans of multiple institutions, although there are still many problems in biological (depletion of fishing grounds) and economic (low monetary profit ranges) terms (Costello et al., 2016). This has resulted in the fishing industry to include some measures such as improving resource efficiency through technological advances or added-value certifications (Boonstra et al., 2018). As a result, there is a growing interest in conducting LCA studies of seafood products (Ziegler et al., 2016), despite the fact that there is still no standardised methodology.

Hence, this document is intended to provide technical guidance with the dual objective of, on the one hand, shedding light on the harmonisation of LCA studies applied to the seafood sector and, on the other hand, estimating a WEF nexus index (WEFni), thus following an integrative perspective for seafood ecolabelling. This composite indicator considers both the negative contribution of seafood products according to their environmental burdens (following a multifootprint point of view: Carbon (CF), Water (WF) and Energy (EF) Footprints), as well as its positive contribution in terms of nutrients intake thanks to the Nutritional Footprint (NF) assessment. For that, the following topics were addressed: (i) selection of the most suitable Functional Unit (FU) to make comparisons among seafood products; (ii) definition of the System Boundaries (SB), identifying the mandatory and optional elements; (iii) consideration of the minimum LCI data required for each stage, as well as the most appropriate allocation factors; (iv) identification of the Life Cycle Impact Assessment (LCIA) methods for calculating the environmental footprints chosen: CF, WF and EF; (v) nutritional characterisation of seafood products for estimating the NF associated; and (vi) integration of the four indicators into a single value (i.e., the WEFni) to be represented in the form of an ecolabel that allows to create a communication channel between producers and customers.

The methodological guidelines introduced through this paper are expected to serve as reference within the NEPTUNUS project. This project aims to implementing a circular economy through the definition of eco-innovation approaches (Laso et al., 2022). Therefore, the NEPTUNUS project partners will apply for the first time the procedure and the ecolabel presented here to a sample of more than 50 case studies. These were based on the production of seafood products through fishing, aquaculture and processing for several countries of the European Atlantic area. Furthermore, the results obtained will be presented and evaluated in a forthcoming scientific publication, thus making available to other LCA practitioners a useful database based on seafood production following a WEF nexus perspective to foster its reproducibility, as well as the improvement of the methodology proposed in future iterations.

For the proper development of this methodological guide, the following documents were considered: (i) ISO 14040 and ISO 1044 standards on LCA (ISO, 2006a, 2006b); (ii) suggestions for updating the Product Environmental Footprint (PEF) method (Zampori and Pant, 2019); (iii) Product Environmental Footprint Category Rules (PEFCR) guidance (European Commission, 2018); (iv) PAS 2050-2:2012 Assessment of Life Cycle greenhouse gas emissions - Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products (BSI, 2012); and (v) ISO 22948:2020 carbon footprint for seafood - Product category rules (CFP-PCR) for finfish (ISO, 2020).

2. Assessing the environmental impacts of seafood products

The two international standards relative to the LCA (i.e., ISO 14040 and ISO 14044) were taken as reference to carried out the assessment of the environmental impacts related to seafood products. Thus, the procedure was divided into 4 steps: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation of results.

2.1. Goal and scope definition

On the one hand, the goal was to propose a common way for the development of LCA studies for seafood products in relation to the calculation of three environmental footprints: CF, WF and EF. On the other hand, the scope covered any activity related to seafood products for human consumption from fisheries, aquaculture or processing sectors, including both fresh and preserved products which use techniques such as freezing, salting or canning. Therefore, the production of fish oil, fishmeal or any other product used for animal feed was excluded.

2.1.1. Functional unit

The FU is the quantified performance to be used as reference basis that allows comparisons to be made when the products obtained by the systems under study can fulfil the same or an equivalent function (ISO, 2006a). Consequently, because the environmental footprint calculation was based on making a comparative assessment of seafood products from an environmental sustainability point of view, the following FU was selected: 1 kg of seafood, either landed at port or produced at the aquaculture or factory gates, including the associated packaging material for processed seafood products.

2.1.2. System boundaries

The different approaches that can be considered in a LCA study according to the stages covered in the seafood supply chain are shown in **Figure 1**. This guide provides flexibility for LCA practitioners to define the SB, but some rules should be applied: (i) the minimum scope will be cradle-to-(port/farm/factory) gate, including surveys for the collection of information from fishing, farming activities or processing facilities, respectively; (ii) life cycle stages included and excluded will be indicated; (iii) a system diagram will be provided; (iv) the FU and reference flow will be consistent with the chosen SB (Helmes et al., 2020).

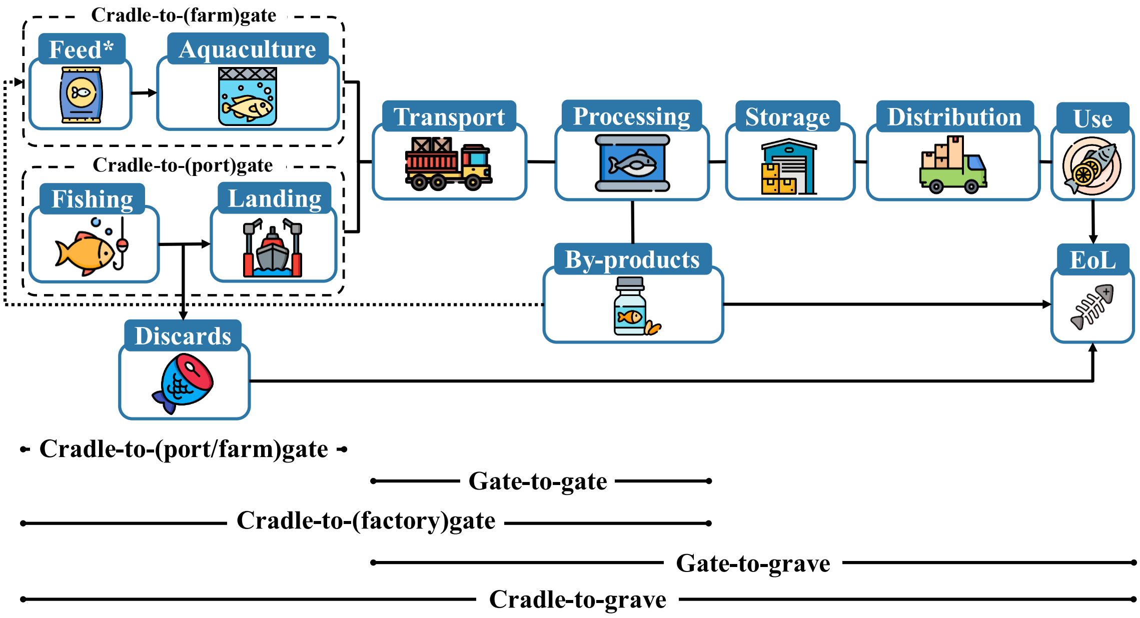

Figure 1. System boundaries of a LCA study according to the covered stages of the seafood supply chain. *External feeding is an optional element in aquaculture, as some of them do not use it (e.g., bivalves or algae). Dotted arrow represents the possibility that feeding comes from by-products.

Therefore, to define the different SB in a LCA study about seafood production, it was considered that up to three different types of systems were possible: fishing, aquaculture and processing.

Regarding the definition of the SB for a fishing system, vessel operations related to the production, transport and consumption of the inputs required (e.g., cooling agents, nets, baits, etc.) should be included. In addition, vessel maintenance also needs to be considered, with vessel construction as an optional element. With this in mind and based on previous scientific articles, the SB for the assessment of the environmental impacts related to fishing activities should include the elements listed in **Figure 2** (Avadí and Fréon, 2013; Villanueva-Rey et al., 2018).

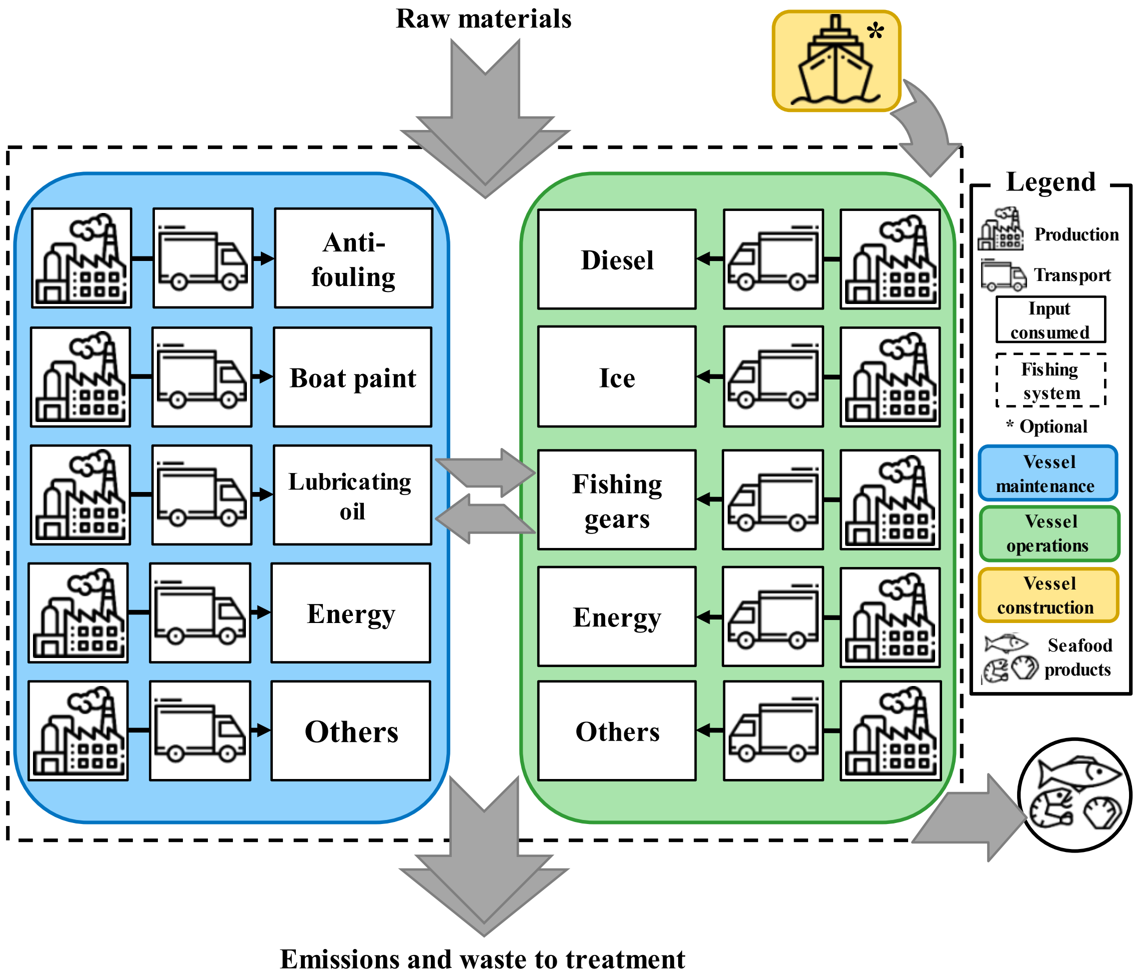

Figure 2. System boundaries for fishing systems in a LCA study.

In the case of aquaculture production systems, the recommended elements are those shown in **Figure 3**, including the aquafeed production where applicable and the aquaculture operations. Concerning the facilities construction, given the difficulty of obtaining high quality data about the capital goods, this is an optional element. In addition, undesirable process outputs, such as wastewater, should be included within the SB, as well as direct emissions produced by the employment of fossil fuels (if these are directly burned in boilers or similar).

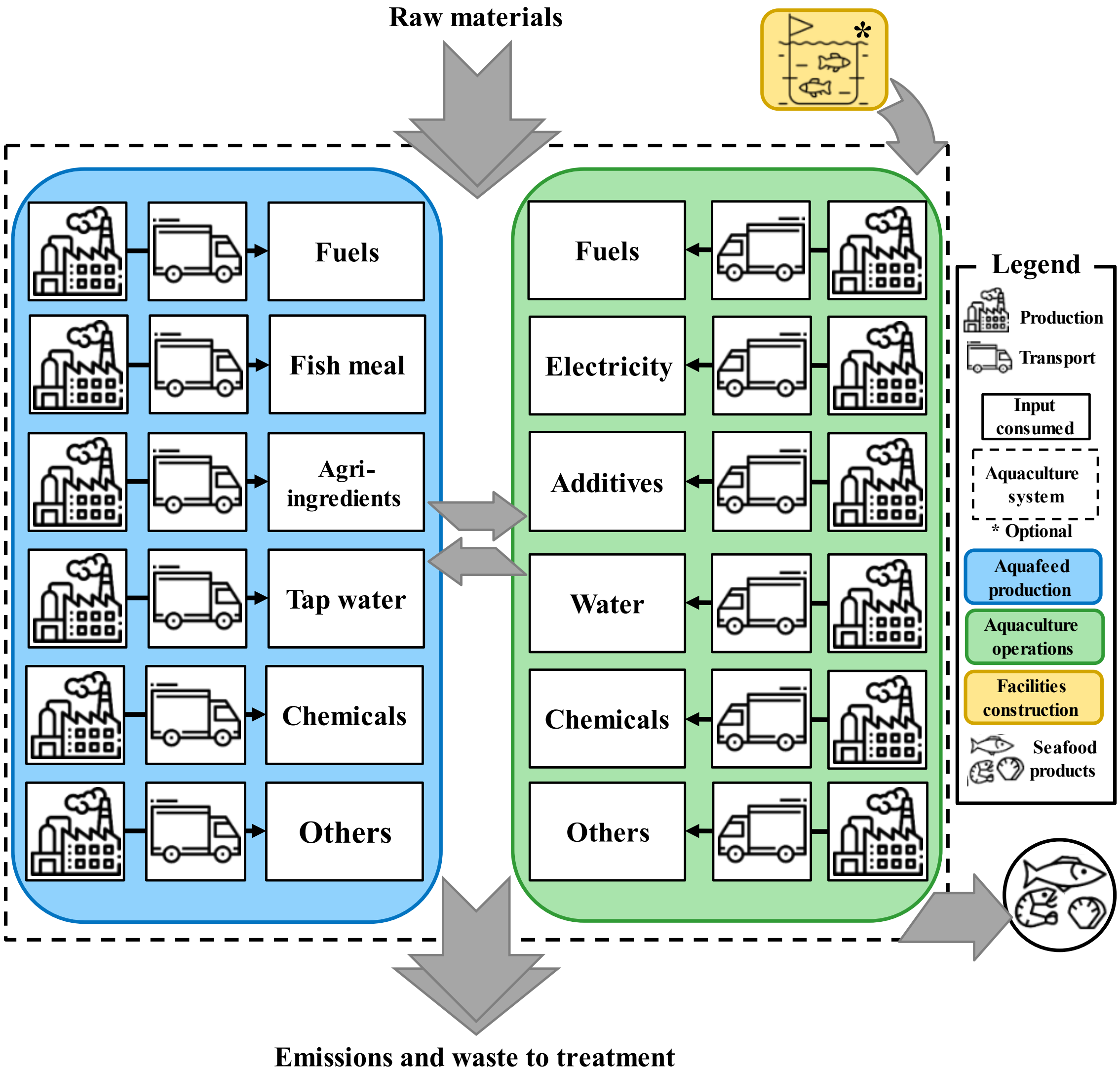

Figure 3. System boundaries for aquaculture systems in a LCA study.

As shown in **Figure 4**, the SB of the processing systems can be divided into the processing stage (e.g., washing, boiling, freezing, etc.) and packaging operations. The most common elements considered within the SB of the seafood processing systems are electricity, fuel (e.g., diesel or natural gas), water, plastics, chemicals and additives (understood as any element that is included in the packaging along with the seafood products, such as sauces). With respect to the packaging operations, all elements that make up the packaging are relevant (whether the seafood is canned or simply filleted). Items used to transport the seafood products through the facility, such as polystyrene trays or wooden pallets should be considering, taking into account the reuse rate and shelf life. Finally, the treatment of the wastes produced should be included within the SB. The most common are organic remains, that can be transformed into products or co-products (e.g., fish viscera and bones), as well as wastes from the packaging operations (e.g., plastics or aluminium).

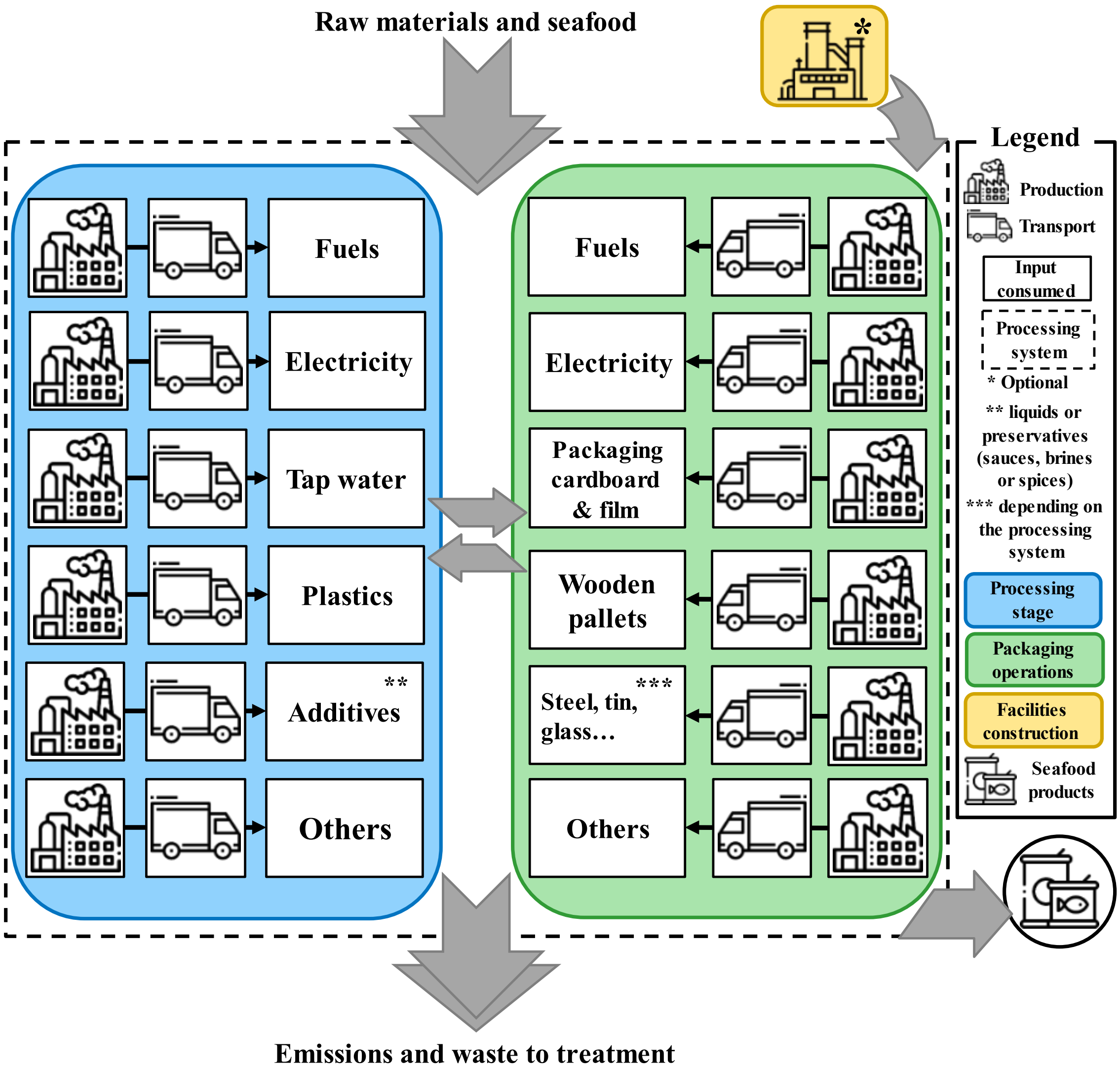

Figure 4. System boundaries for processing systems in a LCA study.

2.1.3. System boundaries exclusions

For LCA studies on seafood products, data on elementary flows to and from systems that contribute at least 99% of the stated environmental impacts shall be included. Then, satisfactory testing of the cut-off rules is done by a combination of expert judgment based on experience with similar systems and a sensitivity analysis where it is possible to understand how the ignored input or output might affect the results. Consequently, processes with small individual impacts (e.g., less than 0.5% of the total) can be ignored. An example of the above is the construction stage of fishing vessels and facilities for aquaculture and processing factories, optional items to be included within the SB in this guide. This is due to their long lifetime, which means that when environmental impacts are relativised to annual production levels, their relative contributions are negligible. However, if good quality data is available, this guide encourages the inclusion of the construction stage. For water consumption, some exclusions can be considered to simplify data collection, such as the volume of water incorporated in seafood meat, as its contribution is not likely to affect the total WF. In addition, as far as aquaculture is concerned, other aspects such as the volume of brackish water abstracted and released in the same receiving water bodies should be disregarded, as it is not addressed in the water use impact assessment.

2.2. Inventory analysis

2.2.1 Data acquisition

Data acquisition is the most relevant step in a LCA study as the LCI directly influences the quality and representativeness of the results (Ciroth et al., 2020). Obtaining primary data should be a priority, although secondary information from scientific studies and databases can be used to fill some gaps and for background processes (e.g., chemical production or electricity generation). To obtain good quality primary data, surveys are recommended to be completed by the responsible agents for further analysis (i.e., skipper for fisheries studies and plant manager in the case of aquaculture and seafood processing facilities).

2.2.2. Emissions modelling

In terms of emissions to air from combustion of fuels (normally, diesel or natural gas), it is highly recommended to collect real measurement data. The above is due to fuel emissions is governed, among other uncontrollable factors, by the variability of sea storms and crew expertise (Vázquez-Rowe and Tyedmers, 2013). In addition, fuel consumption emissions could also be estimated through different approaches available in the literature, such as making use to the updated European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emissions inventory guidebook (EMEP/EEA, 2019).

Regarding the direct emissions to water from the use of antifouling paint, these should be quantified following recommendations in the fisheries LCA literature: two-thirds of the original antifouling paint applied to vessels (Hospido and Tyedmers, 2005).

Regarding Abandoned, Lost or Discarded Fishing Gear (ALDFG), it is highly recommended to estimate it in terms of marine litter at the fishing stage (Vázquez-Rowe et al., 2012). This is based on the fact that ALDFG affects the three dimensions of sustainability: society, economy and environment through certain aspects such as hazards to navigation, ghost fishing and impacts on benthic ecosystems, respectively (FAO, 2019).

In acquiring specific data for the estimation of the WF indicator, the following parameters shall be considered (ISO, 2014): (i) quantities (mass or volume) of water as input (water withdrawal) and output (released into the same watershed in the same period, the same watershed but in a different period, a different watershed or ocean); (ii) types of water resources used (i.e., surface water, seawater, rainwater, groundwater); (iii) data describing water quality parameters (e.g., chemical characteristics); (iv) geographical location of water used or affected (including for water withdrawal or release); (v) emissions to air, water, and soil that impact water quality.

Apart from the above, the next recommendations should be taken into account according to the system evaluated:

- For fishing systems, it is necessary to consider direct freshwater consumption during fishing vessel operations required for conservation (e.g., ice consumption) and during fishing vessel maintenance (e.g., vessel cleaning).
- For aquaculture systems, it is a key factor to account the direct water consumption and quality degradation. In the specific case of closed farming systems, water consumption occurs during egg, larvae or fingerlings production and the growth phase, and includes the water evaporated from the system, incorporated into seafood, and used to wash ponds and facilities. Water quality degradation can occur on-site at aquaculture facilities (Gephart et al., 2017), as well as by the release of eutrophying emissions from the combustion of fuel.

- For processing systems, it is important to be concerned about the direct freshwater consumption that occurs due to water withdrawal for seafood processing activities (i.e., washing, freezing, etc.), water evaporation during the process (i.e., cooking, boiling, etc.), and freshwater deliberated added to the product (e.g., use of water as a preserving liquid for canned products). Direct water quality degradation is mainly related to the discharge of wastewater from the processing activities, as well as by the release of eutrophying emissions from the combustion of fuels.

Data to address electricity mix modelling can be obtained from different sources. First, the supplier-specific electricity product/mix will be obtained directly from the utility provider. In addition, it must be certified in the case of the energy origin assurance statement (e.g., instruments proving the origin of electricity from renewable sources). Second, the country-specific residual electricity mix will be modelled based on reliable data. Third, other relevant data can be found in the publications of the International Energy Agency, as well as other relevant national authorities. For instance, in a Spanish context within the Atlantic area, the database of the Association of Issuing Bodies could be used considering a sufficiently long period to avoid annual energy fluctuations (e.g., three-year period: 2017 to 2019). In addition, the different energy sources consumed for electricity production in Spain should be taken into account (**Table 1**).

Table 1. Demand (%) by energy source in Spain during the 2017-2019 period (AIB, 2019).

Energy	Demand (%)			
	2017	2018	2019	2017-19
Renewables (unspecified)	0.46	0.49	0.00	0.32
Solar	1.75	1.73	1.86	1.67
Wind	1.62	2.42	2.17	2.17
Hydro and Marine	1.10	1.63	0.56	1.12
Geothermal	0.01	0.00	0.00	0.00
Biomass	0.63	0.13	0.77	0.48
Nuclear	30.29	33.89	35.70	33.31
Fossil (unspecified)	1.65	1.82	1.14	1.50
Lignite	4.66	16.62	0.28	7.22
Hard coal	21.10	8.35	10.91	13.44
Gas	31.41	26.95	39.94	32.79
Oil	5.32	5.96	6.67	5.99

2.2.3. Allocation strategies

If a system provides more than one function (i.e., provides several goods or services) it is considered multifunctional. In the literature on LCA applied to seafood, most studies are multiproduct systems because several fishing gears harvest by-catch species and aquaculture facilities use co-products as feed ingredients or are oriented towards a multispecies farming system. In the same way, it is common for processing plants to generate by-products.

In these situations, all inputs and emissions derived from the process must be allocated to the product of interest. In this regard, the PEF method (Zampori and Pant, 2019) and ISO 14044 (ISO, 2006b), propose the following hierarchy of decisions: First, subdivision or expansion of the system should be used to avoid allocation. Second, allocation, which consists of distributing the inputs and outputs of the system among its different products or functions in a way that reflects the relevant and quantifiable relationships between them. Therefore, this guide has opted for the second recommended option, carrying out an allocation process since its purpose was to analyse the environmental impacts related to each specimen.

In relation to the different allocation procedures, some authors point out that mass content is a direct and easy way for sharing the environmental burdens in a LCA food study, while the economic allocation is a good alternative when the fleet is responsible for catching species with large differences in monetary values. Conversely, others authors claim that mass allocation is implausible from a scientific point of view, as well as the economic allocation turns out to be a rough approximation of the amount of material and energy flows associated with the system under study (Ayer et al., 2007; Winther et al., 2009). Consequently, having reviewed the advantages and disadvantages of the different types of allocations available, the allocation rules recommended in this guide are summarized in **Table 2**, given priority to mass allocation over the economic alternative, as it is the simplest and most repeated method for seafood products, avoiding the natural fluctuation of their market price (Vázquez-Rowe et al., 2011). Thus, as a second option and if reliable economic data are available, economic allocation can be applied with a minimum average of three-years period.

Table 2. Allocation rules for the three seafood production systems.

Process	Allocation	Modelling instructions
Fishing co-product allocation	Mass	Despite the selectivity of the fishing gear, several species are caught in addition to the target species. In this sense, the allocation will be made according to the total amount of catches of each specimen (including by-catch species).
Aquaculture co-product allocation	Mass	Aquaculture operations usually focus on the production of a single species, although in some cases it is possible that several species may be produced together. In such cases, the same procedure as for fisheries allocation will apply.
Processing co-product allocation	Mass	Different products can be obtained from the same seafood species. For instance, fillets, tails, fish sticks and croquettes can be obtained from hake. In this case, the total annual production of each production line will be used to establish the allocation factors. In addition, it is important to note that the edible weight should be used to establish the annual production.

2.2.4. End-of-life modelling

The PEF methodology recommends modelling the EoL stage using the Circular Footprint Formula. This formula is promoted with the objective of including the entire life cycle of the material used: the virgin and recycled fractions used in the manufacturing stage, the percentage of the material to be recycled once used, as well as the waste management of the non-recycled part: incineration or landfill disposal (European Commission, 2018). The formula, the description of the parameters that compose it, as well as their respective values are available in Annex C of "Suggestions for updating the Product Environmental Footprint (PEF) method" (Zampori and Pant, 2019) for several material flows.

2.3. Impact assessment

This section describes the different considerations and calculation methodologies selected for each of the environmental footprints that make up the WEFni: CF, WF and EF.

The principles, requirements and guidelines for the quantification and reporting of the CF of a product are found in ISO 14067 (ISO, 2018), consistent with international standards on LCA (i.e., ISO 14040, 14044). In this regard, this guide encourage to use the last version available of the following characterisation method: the 100-year time horizon Global Warming Potentials proposed by the Intergovernmental Panel on Climate Change (IPCC, 2021).

The procedure for calculating the WF of a seafood product will follow the PEF guidance (European Commission, 2018; Zampori and Pant, 2019). Moreover, according to ISO 14046 (ISO, 2014), the WF profile of a product may comprise impact categories related to both freshwater consumption and water degradation. Therefore, the WF of a seafood production system should comprise one category for freshwater consumption (referred to as water use in the PEF method) and two categories for water degradation (freshwater eutrophication and marine eutrophication). The PEF method recommends the following characterisation methods: AWARE (Boulay et al., 2018) for water use impact category, and ReCiPe (Struijs et al., 2009) for the freshwater eutrophication and marine eutrophication impact categories. Normalisation and weighting should also be performed using the respective factors from the PEF guidelines to aggregate the WF impacts into a single indicator resulting from the sum of the weighted results of the three impact categories.

In terms of energy consumption, this can be modelled following different approaches based on the goal and scope of the LCA conducted. Notwithstanding, the assessment method should consider the energy consumed throughout the entire life cycle of a given process, product, or service, both directly and indirectly (e.g., electricity consumption and energy embodied in the manufacture of raw materials, respectively). In this sense, the Cumulative Energy Demand (using Lower Heating Values) shall be the LCIA method implemented to calculate the EF (Frischknecht et al., 2007) since it is aligned with the PEF method.

2.4. Interpretation of results

The results of the three environmental footprints obtained can be interpreted individually to identify the main hotspots of the seafood products assessed from an environmental point of view. Later, the CF, WF and EF together with the NF, will then form the basis for a process of normalisation, weighting and integration to obtain a single indicator, the WEFni.

3. Estimating the nutritional profile of seafood products

Regarding the estimation of a NF applied to seafood products, the objective was to characterize them from a nutrient density point of view. For this purpose, the Nutrient Rich Food (NRF) index in its version NRF9.3 was taken as reference, since it is the indicator that best correlates with the benefits reported by food in terms of the amount of nutrients intake (Fulgoni et al., 2009). This index considers a balance obtained through the positive contribution of 9 nutrients to be Promoted (NP) and the detriment of 3 nutrients to be Limited (NL) (Drewnowski et al., 2009). Therefore, to calculate the nutritional profiles of seafood products, a modified version of the NRF9.3 index was proposed: the NRF12.2 index, based on 12 NP and 2 NL. In comparison with the NRF9.3 index, the NRF12.2 index has excluded one NP (fibre) and one NL (added sugar) because they are absent in seafood. Likewise, four NP were included: one fatty acid (omega 3), two minerals (iodine and selenium) and one vitamin (vitamin D), as seafood products are an important source of these nutrients in the diet (Burk, 2007; Kris-Etherton et al., 2002; Lock et al., 2010; Nerhus et al., 2018).

For the estimation of the NRF12.2 index, the NP and the NL were relativised according to a series of Recommended Values (RVs) and Maximum Recommended Values (MRVs), respectively. For this purpose, the information was collected from different databases, assuming average values between men and women for an adult person (over 18 years of age), appearing collected in **Table 3**. Likewise, the NP were capped at the maximum of the RVs to avoid any profit from over-consumption. By this measure, those seafood products which contain a very large amount of a specific nutrient (i.e., omega-3 in blue fish), do not obtain a disproportionately high NF relative to other fish specimens (i.e., white fish). Finally, the NF of a seafood product "i" was estimated in relation to **Equations 1-3**, being nutrients data on a percentage basis (i.e., referenced per 100 g of final product).

$$NRF12.2_i = NP12_{i,j} - NL2_{i,k}$$ **Equation 1**

$$NP12_{i,j} = \sum_{j=1}^{12} \frac{\left(nutrient_{i,j}\right)_{capped}}{RV_j} \cdot 100$$ **Equation 2**

$$NL2_{i,k} = \sum_{k=1}^{2} \frac{nutrient_{i,k}}{MRV_k} \cdot 100$$ **Equation 3**

Where:

i — seafood product assessed

$NRF12.2_i$ — nutrient rich food index (NRF12.2) of the seafood product "i"

j — nutrients to be promoted (protein, omega 3, K, Ca, Fe, Mg, I, Se and vitamins A, C, D and E)

k — nutrients to be limited (saturated fat and Na)

$NP12_{i,j}$ — contribution of "j" according to the seafood product "i"

RV_j — recommended value for "j"

$\left(nutrient_{i,j}\right)_{capped}$ — "j" of the seafood product "i" (each "j" is capped at its corresponding RV)

$NL2_{i,k}$ — contribution of "k" according to the seafood product "i"

MRV_k — maximum recommended value for "k"

$nutrient_{i,k}$ — "k" of the seafood product "i"

Regarding the processed seafood products, the liquids or preservatives considered as edible (e.g., sunflower oil or tomato sauce) should be included. Otherwise, in the case of non-edible preservative liquids, only the drained weight of the seafood product shall be taken into account (e.g., sardine in brine). Thus, the final NRF12.2 index for processed seafood products shall be equal to the weighted sum of each of its constituent ingredients, i.e. the main food (seafood product) together with the other additional ingredients (see **Equation 4**).

$$NRF12.2_i = \sum_{j=1}^{n} NRF12.2_j \cdot X_j$$ **Equation 4**

Where:

i	seafood product assessed
$NRF12.2_i$	nutrient rich food index (NRF12.2) of the seafood product "i"
j	ingredient present in the content of the processed seafood product
$NRF12.2_j$	nutrient rich food index (NRF12.2) of the ingredient "j"
X_j	percentage of the ingredient "j"
n	number of ingredients that constitute the seafood product "i"

Table 3. Recommended values (RV) and maximum recommended values (MRV) per capita (*EFSA (2017), **FDA (2020)).

Nutrients to be Promoted (NP)		Nutrients to be Limited (NL)	
Nutrient	**RV (g)**	**Nutrient**	**MRV (g)**
Protein*	57	Saturated fat**	20
Omega-3*	0.25	Na*	2
K*	3.5		
Ca*	0.95		
Fe*	0.0135		
Mg*	0.325		
I*	0.000175		
Se*	0.00007		
Vitamin A*	0.0007		
Vitamin C*	0.1025		
Vitamin D*	0.000015		
Vitamin E*	0.012		

4. Ecolabelling seafood products through a Water-Energy-Food nexus index

Once the different indicators were selected and assessed, a process of normalisation, weighting and integration was performed to obtain a composite index integrating them: the WEFni.

On the one hand, normalisation was used to express the values of the indicators in a way that could be compared between the case studies evaluated. In this sense, a linear normalisation in percentage (from 0 to 100) can be made by differentiating between the three seafood production systems (i.e., fishing, aquaculture and processing). However, it is possible to analyse further divisions within the same system (e.g., fishing gears in fishing systems). For this purpose, the maximum and minimum values of each footprint obtained were taken as a reference. Thus, while the seafood product with the lowest environmental footprint in terms of CF, WF or EF was assigned a score of 100, the rest of the seafood products were decreasing in their scores proportionally, considering the cases with the maximum environmental footprints with a normalised value of 0. Conversely, since the NF should be as high as possible, the seafood product with the highest and lowest values will become scores of 100 and 0, respectively (see **Equations 5** and **6**).

$$EnF_{n_i} = \frac{EnF_{max} - EnF_i}{EnF_{max} - EnF_{min}} \qquad \textbf{Equation 5}$$

$$NF_{n_i} = \frac{NF_i - NF_{min}}{NF_{max} - NF_{min}} \quad \textbf{Equation 6}$$

Where:

i	seafood product assessed
EnF_{n_i}	normalised value of the environmental footprints (i.e., CF, WF and EF) for the seafood product "i"
EnF_{max}	maximum value of the environmental footprints (i.e., CF, WF and EF) within the sample assessed
EnF_{min}	minimum value of the environmental footprints (i.e., CF, WF and EF) within the sample assessed
EnF_i	value of the environmental footprints (i.e., CF, WF and EF) for the seafood product "i"
NF_{n_i}	normalised value of the nutritional footprint for the seafood product "i"
NF_{max}	maximum value of the nutritional footprint within the sample assessed
NF_{min}	minimum value of the nutritional footprint within the sample assessed
NF_i	value of the nutritional footprint for the seafood product "i"

On the other hand, regarding the weighting process, the four indicators addressed were considered to equally represent the WEF nexus concept and therefore, with a total of four indicators, each was assigned a relative weighting factor of 25. As regards their integration, a summatory was carried out, thus obtaining the WEFni, which evaluates seafood products through a single value ranging from 0 to 100. The weighting and integration procedures once the normalised values of the footprints appear in **Equation 7**.

$$WEFni_i = \sum_{j=1}^{4} Y_{i,j} \cdot W_j \quad \textbf{Equation 7}$$

Where:

i	seafood product assessed
$WEFni_i$	Water-Energy-Food nexus index of the seafood product "i" (0-100)
j	footprint (carbon, water, energy or nutritional footprints)
$Y_{i,j}$	normalised value of the seafood product "i" for the footprint "j" (0-1)
W_j	weighting factor of the footprint "j" (25 for each footprint)

Finally, the WEFni is expressed in a front-end ecolabelling format to be applied to seafood products with the purpose of serving as a communication channel for consumers, allowing an easy interpretation thorough a single value, as well as a direct comparison with other seafood products. Regarding the success and acceptance of the WEF nexus ecolabel in the market, two key factors must be considered: consumer understanding and acceptance, as well as the interest of retailers in applying it to their seafood products (Weitzman and Bailey, 2018). With this in mind, for its design (see **Figure 5**) it was chosen to represent the WEFni in a percentage range (from 0 to 100%) integrated in a range of 4 colours: red (0-24%), yellow (25-50%), blue (51-75%) and green (76-100%).

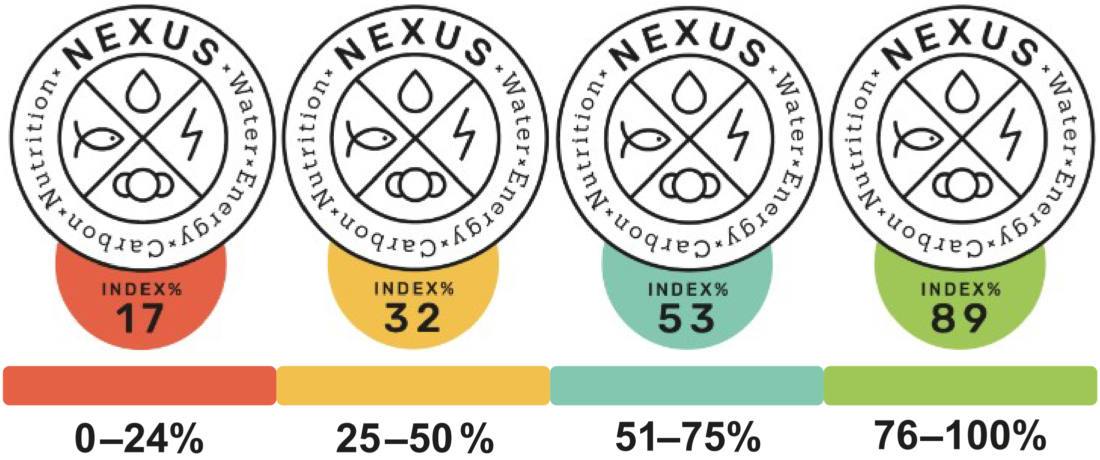

Figure 5. Design of the Water-Energy-Food nexus ecolabel for seafood products applied to four hypothetical case studies.

5. Discussion

5.1. Advantages and disadvantages of the methodological guidelines

Addressing LCA studies applied to seafood products that focus on a single indicator may provide useful information regarding the system assessed. However, in seeking to broaden the scope following a WEF nexus perspective, it becomes crucial to take into account the interdependences between water demand (WF), energy requirements (EF) and nutritional supply of produced seafood (NF) in a context of climate change (CF). Bearing in mind the above, the integration of several indicators through a single value (i.e., the WEFni) varying in a percentage could imply a potential option to gain in the visualisation of the results, especially for the average consumer, who often has no prior knowledge of environmental or nutritional issues. On the downside would be the increased difficulty in identifying major hotspots, such as a non-optimised energy production process or an excess of fuel burned in relation to the catches obtained. The above, in turn, would lead to a lack of precision in masking the individual contributions of some of the indicators (e.g., the individual influences of each nutrient within the NF).

About the selected FU, this was based on the mass content of the seafood products evaluated. However, in this way is nor being represented the true basic function of food, which is to nourish the population (Weidema and Stylianou, 2020). Therefore, there is a changing trend whereby the nutritional perspective is beginning to be considered when conducting environmental impact studies of foodstuffs (McAuliffe et al., 2020). Despite the above, this shortcoming was partially remedied when considering a specific nutritional index for the kind of food under study (NRF12.2). Concerning the established system boundaries, although the case studies for fisheries, aquaculture and processing have been defined in this guide, it would be necessary to include a fourth case because there are currently many hybrid seafood production systems that combine aspects of fisheries and aquaculture (Klinger et al., 2013).

In the context of the procedures followed to obtain the values of the WEFni, the methods for the normalisation and weighting of the footprints are not standardised yet, in addition to ISO does not support its use for LCA comparisons (Andreas et al., 2020). On the one hand, for proposing an external normalisation procedure it would be necessary to consider relevant, official or known parameters to establish general criteria during the decision-making process. In this line, Pizzol et al. (2017) suggest some approaches, such as aggregate, production-based, or consumption-based normalisation. However, the WEFni proposed is based on an internal normalisation with the purpose of carrying out a comparison among seafood products. On the other hand, the weighting process is even more controversial than normalisation, as the decision-making process in this aspect is often based on subjective opinions rather than on scientific grounds. In this context, several weighting techniques can be applied: panel weighting (based on the opinion of a group of people), binary weighting (for zero or equal weights) or monetary weighting (according to monetary valuation), among others (Andreas et al., 2020). Furthermore, despite several mathematical methods being available to determine the weights of a set of indicators in an objective manner, known as multiple-criteria decision analysis (Odu, 2019), it has been decided to prioritise the simplicity by opting to consider the same weight for all indicators, thus opening the door to easy replication of the methodology in other case studies.

Having analysed the advantages and disadvantages of the methodological framework proposed, the main challenge is to build the foundations of a harmonised procedure for assessing both the negative environmental burdens and the beneficial nutritional values of seafood products through a novel single index shown in an ecolabel, allowing comparisons to be made between them. Likewise, this guide represents only the starting point for the NEPTUNUS project consortium to create a database of LCIs scored by the WEFni. However, it is vital to encourage LCA practitioners to adapt the studies of seafood production available in the literature to the particularities of the WEF nexus approach.

4.2. Challenges and priorities of the ecolabel implementation

For producers interested in implementing the voluntary WEF nexus ecolabel, it is necessary to implement a certification scheme. On the basis that the methodological guidelines will be carried out for the first time in a European Atlantic context, it would be crucial for a European eco-certification institution to delegate competences to other national institutions. In this way, through the institutions at national level, companies could implement the WEF nexus ecolabel as a sign of transparency for their consumers, as well as of leadership in environmental policies. Therefore, the WEF nexus ecolabel was designed primarily for public understanding and to encourage producers to carry out the implementation process. For this purpose, it was decided to cover only the WEFni, although it could be interesting to implement some additional information online (e.g., through a code that can be scanned with a smartphone), such as the values of the four footprints along with a brief description of the calculation procedure. Likewise, the ecolabel should be renewed per fishing season (i.e., annually) with the objective that the company to be certified establishes a strategic plan to stay at the forefront of environmentally friendly measures, while creating a distinctive mark with respect to the WEFni obtained compared to other seafood products.

Regarding ecolabels for seafood products, these are increasing as awareness of more sustainable production and consumption grows (Hilger et al., 2019). Consequently, it is expected that “greener” markets are the way forward for the coming years (Prieto-Sandoval et al., 2020). Nevertheless, economic value is often the most influential factor in consumer choice (Barclay and Miller, 2018), so ecolabelling will only gain market share if it allows consumers to positively differentiate the most sustainable products and best practices in order to prioritise it over price. For instance, Neumayr and Moosauer (2021) concluded through a survey that consumers prefer intuitive ecolabels with traffic light colours. In this regard, previous studies reported that consumers are willing to pay 15-30% more if the ecolabel guarantees that the seafood is healthy and sustainably produced (Cantillo et al., 2021). From the point of view of producers, they are sometimes concerned about adding new labels because it may mean higher costs for packaging material or less visibility of their own brand, as well as label overload and gaps in understanding them could lead to confusion (van Asselt et al., 2021).

5. Conclusions

The methodological guidelines described in this work lay the foundations for estimating a new WEFni that attempts to provide a holistic approach for the comparative assessment of seafood products by penalising their environmental burdens while positively considering their nutritional profiles. Furthermore, this composite indicator has been illustrated in an easy-to-understand ecolabel that tries to pave the way for producers and consumers to manufacture and purchase, respectively, seafood products in a reliable manner, communicating their compliance with sustainability criteria.

Likewise, with the goal that the proposed ecolabel can be applied in a near future to the main products of the supply chains in the seafood market, it could be necessary to carried out multiple iterations of the methodology proposed, modifying certain aspects such as the footprints, FU or allocation methods selected, as well as the normalisation and weighting procedures considered to achieve an approximation as close as possible of the true state of the seafood sector under the umbrella of the WEF nexus thinking.

Finally, for bringing this eco-certification to other food sectors, it would be necessary to reconsider what are the best indicators to follow a WEF nexus perspective. For example, a NF proposal should be made that is adapted to the types of food or food sector to be evaluated. In addition, to make the comparison between different food types, the FU should make it appropriate for meals or diets (e.g., serving size or caloric content).

Acknowledgements

This research was supported by the EAPA_576/2018 NEPTUNUS project, supported by Interreg Atlantic area. Some authors belong to CRETUS and the Galician Competitive Research Group (GRC) ED431C 2021/37, co-founded by Xunta de Galicia and FEDER (EU). E.E.B. is funded by Xunta de Galicia PhD Grant (ED481A-2021/164). A.C.D. and P.Q. acknowledge FCT/MCTES for the financial support to CESAM (UIDB/50017/2020 + UIDP/50017/ 2020 + LA/P/0094/2020), through national funds, and to the research contracts CEECIND/02174/2017 and CEECIND/00143/2017, respectively.

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