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Environmental Life Cycle Assessment of Mediterranean Sea Bass and Sea Bream

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Abstract: The aquaculture sector is the fastest growing food production industry, with sea bass and sea bream consisting important exporting goods in the Mediterranean region. This work presents results of a life cycle assessment of Mediterranean sea bass and sea bream, based on primary data collected from a Greek producer. The system boundary included fish feed production and the rearing operation, as well as the packaging and delivery processes, which were neglected in preceding literature studies. The life cycle inventory developed addressed previous data gaps in the production of Mediterranean aquaculture species. Comparison to preceding studies revealed differences on the production inventories and identified methodological choices leading to variability. Packaging and delivery processes were found to contribute approximately 40% towards the global warming score. The production of both sea bass and sea bream was shown to come with high eutrophication impacts occurring from the rearing stage. The feed production was identified as the most environmental impact intensive process throughout the life cycle. Sea bass came with lower environmental impacts per unit live mass, which was reversed when the species were compared on a protein basis. The replicable and transparent model presented here, contributes towards the more accurate quantification of the environmental impacts associated with Mediterranean aquaculture species and supports efforts aiming to promote environmental protection through dietary change.

Keywords: life cycle assessment; environmental impact; fish farming; sea bass; sea bream

1. Introduction

Today's food supply chains are responsible for a quarter of the total anthropogenic greenhouse-gas (GHG) emissions and for significant terrestrial and aquatic ecosystems degradation [1,2]. Animal products consist the most GHG intensive dietary choice, creating a major opportunity for mitigation through dietary change [2,3]. Life Cycle Assessment (LCA) consists a standardized, harmonised and well-developed methodology [4,5] which has been identified as a dominant tool, driving the transition towards sustainable food systems by providing accurate quantifications of the environmental impacts occurring throughout a product's cycle life [6]. In Europe, meat products comprise the most environmentally burdening foods in the average basket [7]. Fish farming is the fastest growing food production industry [8] and offers a viable option in mitigating the enormous amounts of GHG emissions caused by the beef sector, while avoiding the overexploitation of marine fish populations [9]. Mediterranean aquaculture species, sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*), are expected to reach a market volume of 305,000 tonnes by 2030, experiencing a market growth of 4% per year [10]. Greece, the current dominant fish farming country in Europe, is expected to double its production capacity reaching 235,000 tonnes. Most of its production output comes from sea bass and sea bream farming in offshore cages. The growth of Mediterranean aquaculture species production has raised concerns about negative environmental impacts related to farming, such as impacts on water and bottom sediments quality, as well as benthic faunal impact [11,12], interaction with critical or sensitive habitats and species (e.g., seagrass meadows) and with wildlife [13–15].

The increasing market share of aquaculture species and their potential environmental benefits compared to meat products have triggered a growing interest in the scientific community in quantifying their environmental impacts using LCA [16–23]. For the case of Mediterranean aquaculture species, Aubin et al. [24] examined the production of sea bass in marine-based cages in Greece and compared them with other intensive aquaculture production systems. Garcia et al. [25] performed an LCA of sea bass production in Spain, identifying the feed production and fuel consumption as the most environmental intensive processes. Similar results were reported by Garcia et al. [26] for sea bream production, while Abdou et al. [27] performed a comparative assessment of sea bass and sea bream, concluding that the former results in lower environmental impacts in all impact categories. Methodological issues on aquaculture production systems have been reviewed by Bohnes and Laurent [17], who identified restricted system boundaries and limited environmental coverage amongst aquaculture LCA studies.

There are several gaps in the literature concerning the present and future prospect of sea bass and sea bream production. Firstly, even the most seemingly transparent studies either do not provide data on the background production processes or do not report their main Life Cycle Inventory (LCI) at all; thus, they do not allow for deconstruction of their models or reproduction of their results and estimates. Additionally, literature studies have focused on the feed production and rearing stages, with the contribution of packaging and delivery processes to the overall environmental impact of sea bass and sea bream remaining to be quantified. The production scale of previously investigated fish farms does not exceed 1500 tonnes of live fish per year [27], creating an uncertainty concerning the environmental impact of larger scale production systems in dominant aquaculture producing countries, such as Greece. Finally, the literature lacks data on the environmental costs of sea bass and sea bream on a protein basis, thus restricting their comparison with other protein sources.

This article reports the results of a reproducible LCA model, compiled based on primary data collected from a large sea bass and sea bream producer in Greece, with an annual production output of 2815 tonnes for the studied farm. The LCI is reported in detail and background processes were based on the Ecoinvent 3.5 database [28]. The system boundary was expanded to include the packaging and delivery process, in addition to the feed production and rearing, and the results are reported on both live mass and protein basis in order to compare them with preceding literature and benchmark sea bass and sea bream against other protein sources. The impact assessment was performed for nine relevant impact categories and the most important contributions in each case are discussed. The life cycle modelling was performed within the GaBi software.

2. Materials and Methods

2.1. LCA Methodology

Life cycle assessment is a standardised methodology for the determination of the environmental impacts associated with a product, process or activity, widely applied in the energy [29,30], food [31,32] and consumer products [33,34] industries. The ISO 14040 guidelines [35] were followed in order to compile a reliable, transparent and reproducible study. The overarching objective was to analyse the environmental burdens associated with sea bass and sea bream production in Greece. The system boundary was set as cradle-to-gate, with the cradle at the production of fish feed and the gate at end-consumer markets, reflecting a significant portion value chain of aquaculture and related activities for fish food supply. Therefore, the product system included the production of fish feed, the rearing operation, packaging and delivery, as depicted in Figure 1. The functional unit was chosen as one tonne of fish at end-consumer markets, but the impacts were also reported per 100 g edible protein, to enable comparisons with other protein sources. The geographic region boundary was set to Greece, with electricity, material requirements and background processes reflecting the Greek market. The technological boundary was informed by the facility operators and reflects standard aquaculture production practices. The impact assessment was performed based on the CML midpoint characterisation method [36].

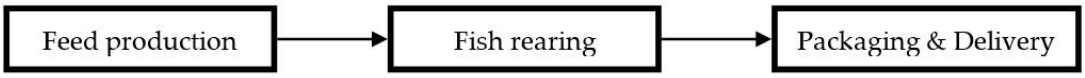


Figure 1. Cradle-to-gate product system studied, including the necessary unit processes to produce sea bass and sea bream in Greece.

2.2. *Inventory Analysis*

In order to fulfil the goals of this study, fish rearing inventories were compiled for sea bass and sea bream and were complemented by feed production, packaging and delivery processes which were common for both species. Primary data were collected from a large sea bass and sea bream producer in Greece (Selonda S.A, Peania, Greece). The Ecoinvent 3.5 database [28] was complemented with preceding literature findings to model the fish production system within the GaBi software. The hatching and nursing phase includes activities taking place in onshore facilities, stock maintenance and phytoplankton and zooplankton production. Given the nature of the operations and that the fish is transferred to the rearing facility when it reaches a mass of 2 g, it is reasonable to assume that the environmental impacts of the hatching and nursing phase are insignificant compared to the rearing operation, growing fish from 2 g to 600 g. Therefore, it was excluded from the product system, in line with preceding literature studies [25,26]. This assumption is further supported by the fact that a previous study focusing on rainbow trout production reported a negligible contribution of the hatchery to the life cycle climate impact and a 2% contribution to the eutrophication impact [37]. The inventories for the feed production, fish rearing and packaging and delivery processes are presented in detail below.

The foreground data for the fish rearing operation were provided directly by the facility operators and are summarised in Table 1. The facility is located in Sofiko, Corinth, Greece and consists of 6 circular net cages (33,600 m^3) for the production of sea bass and 64 circular net cages (371,900 m^3) for the production of sea bream. The fish grows from 2 g to 600 g within 24 months on average. The annual production of sea bass and sea bream in 2017 was 208 and 2607 tonnes, respectively. The Feed Conversion Ratio (FCR) for the sea bass and sea bream was reported as 1.85 and 2.5, respectively. The feed is delivered to the facility in 1 tonne bulk bags made of polypropylene. The total circular net cage diameter for sea bream and sea bass rearing is 1661 m and 153 m, respectively, and was expressed per mass of live fish produced by assuming a facility lifetime of 15 years. Diesel and petrol are combusted in the farm to run power generation machinery, boats and cranes. Electricity is consumed mainly in fridges and refrigerators. The main direct emissions of the operation are phosphorus and nitrogen to sea water.

According to the plant operators, depending on the size of the fish, feeds of different composition and granulometry are supplied. Additionally, the same type of feed is used for sea bass and sea bream rearing, consisting of 43% to 56% protein, depending on the size of the fish. For fish feed production, the inventory for sea-bass feed of Aubin et al. [24] was adopted as representative for Greece and was complemented by the energy and facility requirements of tilapia feed production, as included in the Ecoinvent database. The main inputs to the feed production inventory together with the background processes are summarised in Table 2.

Table 1. Inventory for sea bream and sea bass rearing farm based on primary data from a Greek aquaculture producer. GLO corresponds to a global dataset; RER corresponds to a European dataset; GR corresponds to a Greek dataset; RoW corresponds to the rest of world.

Quantity	Units	In		Out		Ecoinvent Process
		Sea Bream	Sea Bass	Sea Bream	Sea Bass	
Live fish	**kg**			1000	1000	
Hatchling	kg	7	12			Burden-free from technosphere
Fish feed	kg	2500	1850			Table 2
Feed packaging	kg	1.3	0.9			GLO: market for polypropylene, granulate
Collar cage	m	0.04	0.05			GLO: market for floating collar cage
Diesel production	L	38	72			RER: market group for diesel
Diesel combustion	MJ	1400	2700			GLO: diesel, burned in fishing vessel
Petrol production	L	5	14			RER: market for petrol, unleaded
Petrol combustion	MJ	190	510			market for petrol, unleaded, burned in machinery
Electricity	kWh	740	740			GR: market for electricity, medium voltage
Waste feed packaging	kg			1.3	0.9	RoW: waste polypropylene
Phosphorus	kg			30	22	Phosphorus[inorganic emissions to sweater]
Nitrogen	kg			172	127	Nitrogen (as total N)

Table 2. Fish feed production inventory inspired by Aubin et al. (2009) and the Ecoinvent database.

Quantity	Units	In	Out	Ecoinvent Process
Fish feed	kg		1000	
Fish oil	kg	80		GLO: market for fish oil
Fish meal	kg	420		GLO: market for fishmeal, 65–67% protein, from anchovy
Maize grain	kg	80		GLO: market for maize grain, feed
Protein feed, 100% crude	kg	50		GLO: market for protein feed, 100% crude
Soybean meal	kg	150		GLO: soybean meal to generic market for protein feed
Wheat grain, feed	kg	220		GLO: market for wheat grain, feed
Electricity, medium voltage	kWh	78.2		GR: market for electricity, medium voltage
Heat, natural gas	MJ	627		GR: heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
Heat, non-natural gas	MJ	210		RoW: market for heat, central or small-scale, other than natural gas
Oil mill	units	8.63×10^{-7}		RoW: oil mill construction

When the fish reaches a commercial weight, it is slaughtered and delivered to the packaging facility for further processing. There, it is packaged in boxes made of styrofoam; each 0.7 kg box includes approximately 6 kg of fish. The fish is transported to end-consumer markets and the packaging is removed before it reaches the shelf. The inventory for the packaging and delivery process is shown in Table 3. The materials requirement was based on the mass composition of the packaged fish. The electricity requirement was provided by the company, with 66% of it powering fridges and refrigerators, 7% powering the packaging processes and the remaining corresponding to supporting machinery. The facility requirement was modelled based on a generalised Ecoinvent inventory for fish freezing plants. The fish was assumed to be transported for 300 km to reach end-consumer markets, where it is unpackaged and sold. This transportation distance corresponds to the average from Sofiko to the two major city centres of Greece, Athens and Thessaloniki.

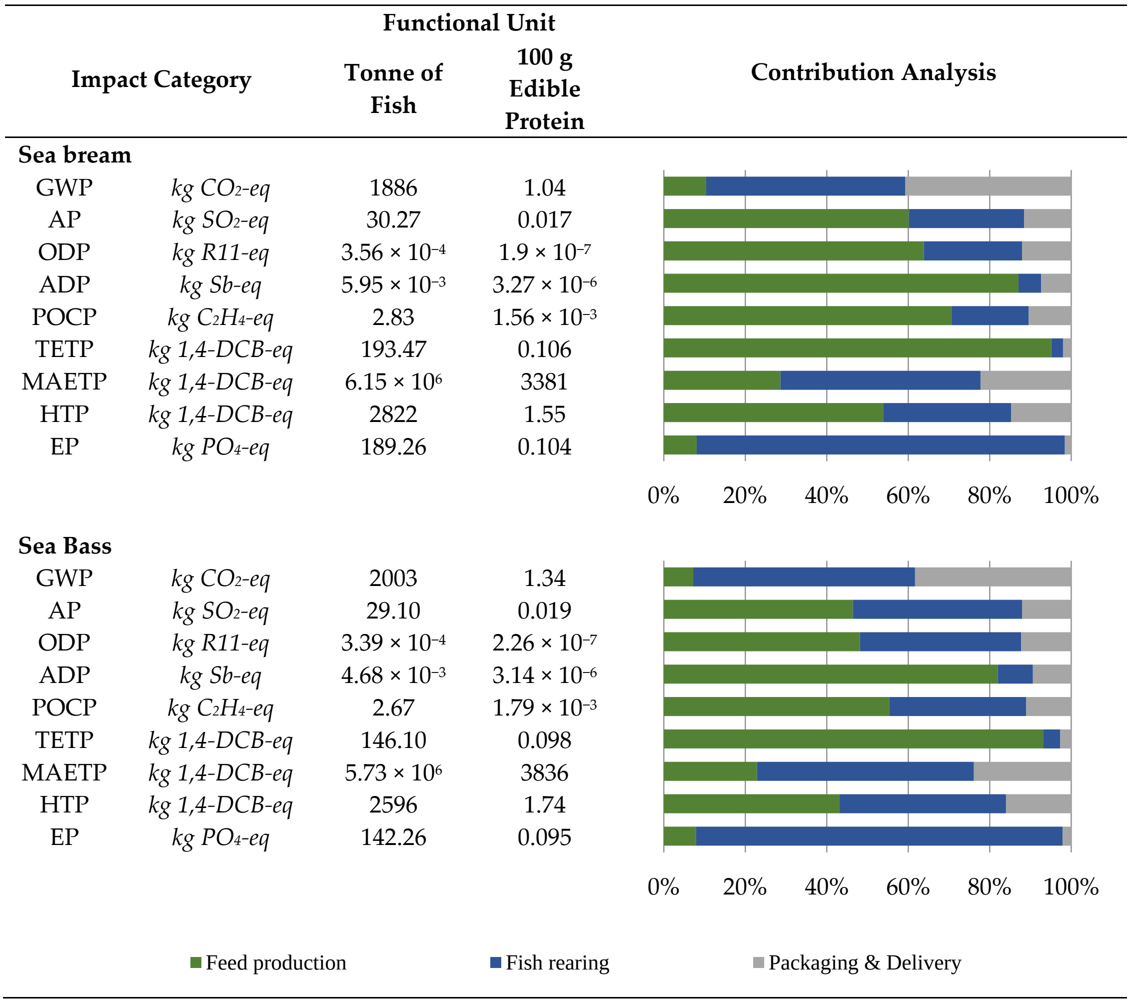
In order to report the results for the two species on a 100 g edible protein basis the ratio of edible protein per live mass was calculated. The carcass yield (edible mass per total live mass) for sea bass and sea bream were at 88.9% [38] and 88.3% [39], respectively. The protein content of the two species was 20.6 wt% for sea bream and 16.8 wt% for sea bass [40]. Combining the two quantities led to the calculation of 100 g edible protein content per ton of live fish as 1819 for sea bream and 1494 for sea bass.

Table 3. Inventory for the packaging and delivery process inspired by primary data from the facility operators.

Quantity	Units	In	Out	Ecoinvent Process
Fish, at seller	kg		1000	
Live fish	kg	1000		
Styrofoam	kg	110		RoW: polystyrene production, expandable
Electricity, medium voltage	kWh	320		GR: market for electricity, medium voltage
Packaging factory	units	2.2×10^{-3}		RoW: fish freezing plant construction and maintenance
Transportation	tkm	300		GLO: market for transport, freight, lorry with refrigeration machine, 7.5-16 tonnes, EURO5, R134a refrigerant, cooling
Waste expanded polystyrene	kg		110	GR: market for waste polystyrene

3. Results

The results for sea bass and sea bream production are reported in Figure 2. The contribution of the dominant life cycle stages to each impact category is presented and further disaggregated to key contributing background processes.



Impact Category		Functional Unit: Tonne of Fish	Functional Unit: 100 g Edible Protein
Sea bream			
GWP	*kg CO_2-eq*	1886	1.04
AP	*kg SO_2-eq*	30.27	0.017
ODP	*kg R11-eq*	3.56×10^{-4}	1.9×10^{-7}
ADP	*kg Sb-eq*	5.95×10^{-3}	3.27×10^{-6}
POCP	*kg C_2H_4-eq*	2.83	1.56×10^{-3}
TETP	*kg 1,4-DCB-eq*	193.47	0.106
MAETP	*kg 1,4-DCB-eq*	6.15×10^{6}	3381
HTP	*kg 1,4-DCB-eq*	2822	1.55
EP	*kg PO_4-eq*	189.26	0.104
Sea Bass			
GWP	*kg CO_2-eq*	2003	1.34
AP	*kg SO_2-eq*	29.10	0.019
ODP	*kg R11-eq*	3.39×10^{-4}	2.26×10^{-7}
ADP	*kg Sb-eq*	4.68×10^{-3}	3.14×10^{-6}
POCP	*kg C_2H_4-eq*	2.67	1.79×10^{-3}
TETP	*kg 1,4-DCB-eq*	146.10	0.098
MAETP	*kg 1,4-DCB-eq*	5.73×10^{6}	3836
HTP	*kg 1,4-DCB-eq*	2596	1.74
EP	*kg PO_4-eq*	142.26	0.095

Figure 2. Cradle-to-gate environmental impacts for sea bass and sea bream production, reported quantitatively for two functional units and disaggregated to the feed production, rearing and packaging & delivery contributions. GWP: Global Warming Potential, AP: Acidification Potential, ODP: Ozone Depletion Potential, ADP: Abiotic Depletion Potential, POCP: Photochemical Oxidant Creation Potential, TETP: Terrestrial Ecotoxicity Potential, MAETP: Marine Aquatic Ecotoxicity Potential, HTP: Human Toxicity Potential, EP: Eutrophication Potential.

For sea bream, feed production, rearing and packaging and delivery contributed to the Global Warming Potential (GWP) by 10%, 49% and 41%, respectively. 77% of the GWP for sea bream rearing arose from electricity production and 13% from diesel combustion in the facility. The packaging and delivery process' GWP was primarily driven by polystyrene production (48%) and electricity (40%). Fish oil and meal production consisted the dominant contribution to the fish feed production GWP. The scenario is similar for sea bass production, where the GWP is increased because of higher diesel and petrol consumption during the rearing process.

The Acidification Potential (AP), Ozone Depletion Potential (ODP), Abiotic Depletion Potential (ADP) and Photochemical Ozone Creation Potential (POCP) were dominated by the feed production process. For the latter, fish meal, oil, soybean meal and wheat grain production consisted the dominant contributions towards those impact categories. Important contribution also arose from the rearing operation, driven by the consumption of diesel and electricity in the sea farm. The contribution of fish feed production towards AP, ODP, ADP and POCP for sea bass was lower compared to sea bream, mainly resulting from the decreased FCR of the former. More than 93% of Terrestrial Ecotoxicity Potential (TETP) arose from the feed production process, for both sea bass and sea bream. The key contributing processes towards TETP during feed production were soybean meal production (66%), wheat grain production (20%) and protein feed (10%). For both sea bass and sea bream, approximately half of the Marine Aquatic Ecotoxicity Potential (MAETP) came from fish rearing and is directly linked to its electricity requirement. Important contributions also arose from the feed production and packaging and delivery processes, which were also linked to their electricity requirement. Similarly, the electricity and fossil fuel requirement contributed towards the Human Toxicity Potential (HTP). The Eutrophication Potential (EP) was dominated by fish rearing and is directly linked to the emissions of N and P during the operation.

Overall, on a live mass basis, sea bass production scored lower on all environmental categories except from GWP. This is directly linked to the improved FCR during sea bass rearing, as reduced FCR result in a lower amount of feed required to grow fish. The GWP of sea bream production was lower due to the decreased petrol and diesel consumption in the rearing facility. This is attributed to the production scale of sea bream compared to sea bass, with the former being higher by an order of magnitude, at 2607 tonnes per year. As diesel and petrol are used to power supporting machinery such as power generators and boats, their consumption does not increase linearly with increased production scale, leading to lower requirements per unit output. On a 100 g edible protein basis, sea bream production scored lower on all environmental impacts compared to sea bass due to its increased protein content.

4. Discussion

4.1. Sea Bass and Sea Bream Rearing Inventories

The fish rearing operation lies in the heart of the sea bass and sea bream production systems and has been examined by a series of preceding literature studies [24–27]. In this study the FCR was fixed at 2.5 for sea bream and 1.85 for sea bass. Aubin et al. [24] reported an FCR of 1.77 for sea bass rearing in Greece, while a Tunisian study reported an FCR of 1.85 and 1.88 for sea bream and sea bass, respectively [27]. Garcia et al. [26] reported an FCR of 2 for sea bream production in Spain and, more recently, Garcia et al. [25] reported an FCR of 1.5 to 1.9 for sea bass, depending on the growing stage. As the FCR depends on a series of environmental factors, those variations amongst studies are reasonable. Additionally, sea bream appears to have a higher FCR than sea bass in the studied farm, which is mainly attributed to the different average commercial weight reached by the two species, as the environmental and feeding conditions are similar. Due to limited information, it is not possible to conclude whether environmental conditions, such as low oxygen levels, or the different commercial weight reached by the fish resulted in higher FCRs for sea bream amongst literature studies.

Strongly connected with the FCR, the amount of N and P emitted to sea water is detrimental to the eutrophication impact of Mediterranean aquaculture species. Aubin et al. [24] theoretically calculated the amount of N and P emitted per tonne of live fish produced, as 101.7 kg tonne^{-1} of live fish and 16.7 kg tonne $^{-1}$ of live fish, respectively. The emissions to sea water were further partitioned to solid and dissolved fractions; a similar approach was followed by Abdou et al. [27]. In this study, the total amount of N and P emitted during sea bass rearing was reported by the plant operators as 127 kg tonne^{-1} of live fish and 22 kg tonne^{-1} of live fish. The emissions were not partitioned between solid and dissolved fractions, as no such options exist in GaBi and Ecoinvent. Garcia et al. [25] reported the emissions of N and P for sea bass production as 105.27 and 17.21 kg tonne^{-1} of live fish, respectively. For sea bream production, this study reports emissions 172 kg N tonne^{-1} of live fish and 30 kg P tonne^{-1} of live fish. Garcia et al. [26] reported emissions of N and P of 119.59 and 5.93 kg tonne^{-1} of live fish, respectively for sea bream, with the differences being primarily attributed to the 25% higher FCR used in their study. Additionally, preceding studies have modelled an oxygen input to the rearing operation [24,25,41] in the form of liquid oxygen, which was supplied in order to avoid any stress occurring from low oxygen levels [42]. In the studied farm, optimal feeding conditions are achieved without an additional oxygen supply. It was, therefore, not taken into consideration in the fish rearing inventory.

The amount of energy required during the fish rearing operation is crucial in the overall GWP, AP, ODP, ADP, PMCP, MAETP and HTP. In this study, the electricity required for sea bass and bream rearing was fixed at 740 kWh tonne^{-1} of live fish. Garcia et al. [25,26] assumed that the fish rearing plant is exclusively powered by diesel, reporting 511.34 kg of diesel tonne^{-1} of live fish required for sea bass production [25] and 444.33 kg of diesel tonne^{-1} of live fish for sea bream [26]. In this study, 31.6 kg and 59.9 kg of diesel were combusted to produce a tonne of sea bream and sea bass, respectively.

4.2. Environmental Impacts Comparison

Benchmarking the results against preceding literature findings consists a challenging task due to lack of transparency, different characterisation methods and system boundaries. Aubin et al. [24] employed their own characterisation method, introducing novel impact categories, while the remaining literature studies are based on the CML method. The system boundaries in the literature mainly include facilities, energy and material requirement for the fish feed production and rearing processes. To directly compare our results to preceding literature findings, as shown in Table 4, the contribution of the packaging and delivery process was excluded in order to express the environmental impact per tonne of live fish weight.

Table 4. Environmental impacts for producing a tonne of live sea bream and sea bass as reported across literature studies.

Impact Category	Units	Sea Bass				Sea Bream		
		Aubin et al. [24]	**Abdou et al. [27]**	**Garcia et al. [25]**	**This Study**	**Garcia et al. [26]**	**Abdou et al. [27]**	**This Study**
GWP	*kg* CO_2*-eq*	3601	3182.22	7293	1235 *	7124	3668.65	1118 *
AP	*kg* SO_2*-eq*	25.3	18.85	44.15	25.6	38.46	21.61	26.77
ODP	*kg R11-eq*	n/a	n/a	6.2×10^{-4}	2.97×10^{-4}	13×10^{-4}	n/a	3.05×10^{-4}
ADP	*kg Sb-eq*	n/a	n/a	1.81×10^{-3}	4.24×10^{-3}	1.65×10^{-3}	n/a	5.5×10^{-3}
POCP	*kg* C_2H_4*-eq*	n/a	n/a	1275	2.38	1.12	n/a	2.54
TETP	*kg 1,4-DCB-eq*	n/a	n/a	11.99	142.15	n/a	n/a	189.5
MAETP	*kg 1,4-DCB-eq*	n/a	n/a	1×10^6	5.73×10^6	n/a	n/a	4.78×10^6
HTP	*kg 1,4-DCB-eq*	n/a	n/a	837	2180	n/a	n/a	2406
EP	*kg PO4-eq*	108.85	91.03	115.23	139.3	81.79	98.86	186.3

* This study's reported GWP takes into account the carbon absorbed during fish feed production.

This study's reported GWP for sea bass and sea bream production appears to be at the lower end of the spectrum compared to preceding literature findings. For sea bass production, Aubin et al. [24] reported a GWP of 3601 kg CO_2-eq tonne^{-1} of live fish which is almost three times higher than this study's reported sea bass GWP (excluding the packaging and delivery contribution). Similarly, Abdou et al. [27] reported a GWP of 3668.65 kg CO_2-eq tonne^{-1} of live fish for sea bream, which is also 3 times higher. These studies have identified the feed production as the dominant contributor to GWP, which is not the case for our study. As the feed production inventory in this study is taken from Aubin et al. [24], the main difference is traced to the impact assessment calculations. Specifically, excluding the carbon absorbed during the cultivation of crops has a tremendous impact on the calculated GWP. For sea bass production, excluding biogenic carbon results in a GWP of 3365 kg CO_2-eq tonne^{-1} live fish, which is very similar to the previously reported results from Aubin et al. [24], and in a GWP of 3985 kg CO_2-eq tonne^{-1} live fish for sea bream, which is very close to the value reported by Abdou et al. [27]. The GWP reported by Garcia et al. [26] and Garcia et al. [25] are 7124 kg CO_2-eq tonne^{-1} live fish and 7293 kg CO_2-eq tonne^{-1} live fish for sea bass and sea bream, respectively. The authors have identified the feed production chain as the dominant contribution towards the GWP and the exemption of biogenic carbon from their calculations has probably led to such high numbers. Additionally, they report very high amounts of diesel combusted to maintain the facility in the order of 500 kg tonne^{-1} live fish, which strongly contribute towards the overall GWP. Such high fossil fuel requirement is believed to occur from the low production scale of the studied farms, which is in the order of 1000 tonnes per year, as discussed in Section 3. The differences in AP, ODP, ADP, POCP and TETP are reasonable given the different energy sources assumed in each study and the different feed production inventories. The MAETP and HTP are directly linked to the electricity requirement which explains the higher values reported by this study. The eutrophication impacts reported for sea bass are within 30% of previously reported values. For sea bream, the reported EP is approximately two times higher compared to previously reported values. This is primarily attributed to the much higher FCR of our study (2.5) compared to 1.85 reported by Abdou et al. [27] and 2 reported by Garcia et al. [26].

One of the primary goals of this study was to expand the system boundary of sea bass and sea bream production to include packaging and delivery processes. This was done based on a combination of primary data and engineering calculations. For both sea bass and sea bream, the packaging and delivery process contributed approximately 40% towards the total GWP. Its contribution was driven by the electricity consumption and the polystyrene production process. The packaging and delivery contributed more than 10% towards all environmental impact categories, except from EP, TETP and ADP. It is therefore crucial to include this contribution in the determination of the environmental impacts of sea bream and sea bass production and this study provides the means to do that.

4.3. Reducing the Environmental Impact of Protein Sources

For the two species, the reported GWP on a 100 g edible protein basis ranges from 1.04 to 1.34 kg CO_2-eq for sea bream and sea bass, respectively. The higher GWP footprint of sea bass is partly attributed to its lower protein content, which is closely related to nutrition, living area, fish size and other environmental conditions [43]. Therefore, the difference in protein content is considered to be site specific and might differ between farms. The reported GWP values for sea bass and sea bream are lower than those of ruminant meat and very similar to poultry and pork [2,44]. They also appear to be at the lower end of the spectrum for aquaculture products [44]. However, the EP mainly occurring from fish farming, ranks sea bass and sea bream in the higher end compared to other protein sources. This impact can be mitigated through a series of modifications on the feeding techniques. Optimising the FCR can lead to lower EP, which can be achieved through automation and the establishment of optimal temperature, oxygenation conditions and current velocities. FCR is related to water temperature, fish size and feeding rhythm. In Greece, FCRs are generally higher in winter due to low temperature and increase as fish is getting bigger. Additionally, the majority of the GWP and MAETP impacts are traced back to the electricity consumption of each process. Greek electricity generation is currently dominated by coal, but the country is on track to achieve 90% renewable electricity by 2050 [45]. The increased penetration of renewables in the Greek electricity sector will gradually reduce the climate impact of its aquaculture industry.

5. Conclusions

A life cycle inventory for sea bream and sea bass production was constructed based on primary data from a large-scale producer in Greece. The standard system boundary of preceding literature studies was expanded to include packaging and delivery processes, which were shown to contribute approximately 40% to the overall GWP of both sea bass and sea bream. Feed production consisted the most environmental impact intensive process, while important contributions arose from the electricity and fossil fuel requirement throughout the life cycle, and the direct emissions of N and P during the fish rearing stage. Sea bream was shown to come with a higher environmental cost compared to sea bass, with that being reversed when comparing the two species on an edible protein basis due to the larger protein content of the former. The detailed comparison to preceding studies demonstrated that different reporting methods can significantly affect the GWP of Mediterranean aquaculture species, which is particularly important when comparing alternative protein sources. The replicable model presented here offers robust means of decision making that complement scientific and engineering developments, aiming to promote sustainability through dietary change.

Author Contributions: Conceptualisation, E.K. and P.A.; methodology, E.K.; formal analysis, E.K.; data curation, D.M. and P.A.; writing—original draft preparation, E.K.; writing—review and editing, A.K. and P.A. All authors have read and agreed to the published version of the manuscript.

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