Research Article

Life cycle assessment of seabass and meagre in marine cage farming - From feeding plant to harvesting

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Contributing Editor: Stelios SOMARAKIS

Abstract

Aquaculture is related to environmental impacts, both locally and globally. The purpose of this study was to identify environmental hotspots linked to fish feeds of various granulations, in seabass and meagre farming using Life Cycle Assessment (LCA) approach, given that recent studies suggest that fish feed is the predominant factor affecting marine fish farming. This, in turn, enabled a detailed comparison of environmental performance throughout the rearing cycle, in both species. LCA was applied to the production process of fish feeds taking into account the quantities of raw materials, heat and energy needed for the production of feed. Similarly, LCA was applied to cage farms in Greece, involving the quantity of feed per size class, energy and fuel needed for the production of one tonne of seabass and meagre, respectively. The smaller sized feed (SSF) class distributed to the fry, performed better compared to the medium (MSF) and large sized feed (LSF) classes fed to juveniles/adults, in relation to various environmental impact indicators. In medium and large sized feeds, the main negative contributor was the use of sunflower meal, while small sized feed affected these indicators through higher electricity demands and the quantity of fishmeal. A comparison between seabass and meagre revealed that meagre had a significantly lower impact on all eighteen environmental impact indicators. This should be attributed to reduced feed conversion ratio and lower fry requirements compared to seabass. Improvements in cultivation methods of raw materials, optimized reductions of raw materials of marine origin and improved feeding management could contribute to overall ecological sustainability of the sector.

Keywords: Life Cycle Assessment; seabass; meagre; feed granulation; aquaculture.

Introduction

Aquaculture is a flourishing industry that plays a major role in food production, food security, employment and economic development (Massa *et al*., 2018). Accordingly, its contribution to fish protein intake, which is approximately 8.8% of world animal protein consumption (FAO, 2020), is expected to rise, in order to fulfil global demand of rising world population (Béné *et al*., 2015). In Mediterranean countries in particular, aquaculture production has grown steadily in recent decades and this trend is expected to continue. On the other hand, sea cage farms are located in coastal areas mainly and, therefore, sustainable coastal zone management strategies are required for an environmentally-friendly aquatic food production sector (Børresen, 2013; Ababouch, 2015).

In Greece, intensive marine fish farming has a 36-year old successful record. Gilthead seabream (*Sparus auratus* Linnaeus, 1758) and Mediterranean seabass (*Dicentrarchus labrax* Linnaeus, 1758) production reached 120,500 tonnes in 2019. Minor volumes of around 4,300 tonnes of total production consist of 'new' candidate species, with meagre (*Argyrosomus regius* Asso, 1801) constituting almost half of such production (FGM, 2020). Meagre is a promising species for Mediterranean fish farms (Estevez *et al*., 2018); it adapts well in captivity, achieves relatively fast growth rates (Costa *et al*., 2013; Ribeiro *et al*., 2013) and higher prices (Saavedra *et al*., 2015) compared to seabream and seabass. It can grow up to 1 kg/year (Estevez *et al*., 2018) under good rearing conditions and accumulates low amounts of mesenteric and muscle lipids compared to other farmed species. Moreover, it is characterized by high fillet yield and a balanced fatty acid profile (Grigorakis *et al*., 2011; García Mesa *et al*., 2014).

In intensive sea cage farming, earlier environmental studies have focused mainly on the local impacts of farms and they were related to the release of organic waste derived mainly from feed (in dissolved and particulate forms) (Pitta *et al*., 1998). However, many other impacts

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related to several wider/global-scale industrial processes are involved in fish farming (e.g. extraction of raw materials, feed production, construction and use of infrastructure and equipment; Luna *et al*., 2013; Farmaki *et al*., 2014; Ottinger *et al*., 2016). These environmental burdens are responsible for emissions of air pollutants that cause environmental problems, such as global warming, air quality degradation, acidification and eutrophication, which cause damage to ecosystems, loss of biodiversity and human health problems (e.g. respiratory and cardiovascular; WHO, 2003).

In view of the aforementioned issues, Life Cycle Assessment (LCA) is a useful tool; it can be used for quantitative assessment of materials, energy flows and impacts of production systems and evaluation of the environmental performance of products and/or services. It is an International Organization for Standardization (ISO) (ISO, 2006a,b) environmental management technique (ISO:14000 family and specifically ISO:14044, 14046). It takes into account a product's life cycle; from the extraction of resources, processing of raw materials, production, use, possible recycling, to the final disposal of the remaining wastes. In other terms, LCA is a material and energy balance application, combined with environmental assessment of the impacts related to the inputs and outputs of the production system. Therefore, LCA provides criteria for decision-making on issues such as environmental product development, policy making and strategic planning. It has been promoted in European directives as a robust quantitative tool and a keystone decision-making process for producers and stakeholders. It is used increasingly to assess the environmental impacts of fish farming (Bohnes & Laurent, 2019) and can provide industry stakeholders with information to improve process efficiency and identify production stages that perform well and those that can be improved.

During the past 16 years, assessment of aquaculture feeds by LCA has been applied to various farmed species (Papatryphon *et al*., 2004; Pelletier & Tyedmers, 2007; Boissy *et al*., 2011; Iribarren *et al*., 2012; Samuel-Fitwi *et al*., 2013; Avadí *et al*., 2015; Cashion *et al*., 2016; Avadí *et al*., 2019; Le Feon *et al*., 2019). However, among the limited studies on seabass/seabream feeding, none have assessed the commercially available granulations used typically during the entire fish production cycle (i.e. three feed size classes; however, see García García *et al*., (2019) who involved two feed size classes).

Concerning fish species of Mediterranean origin, earlier LCA studies on seabass farming concerned assessment against trout and turbot in different production systems (Aubin *et al*., 2009) and a comparison between two different land-based growing facility systems (Jerbi *et al*., 2012). More recent works have dealt with a comparison between seabass and seabream, both fed on a single type of feed (Abdou *et al*., 2017), the design of a bioeconomic model under different types of quota commonly used in Europe (Besson *et al*., 2017), the identification of the influence of variability in farming practices on environmental performance (Abdou *et al*., 2018) and, finally, the explanation of the variability of potential environmen-

tal impacts (García García *et al*., 2019). Additionally, a recently published work compared seabass farming in two cage farms (one in Thesprotia-Greece and one in Vlore-Albania; Konstantinidis *et al.*, 2020). The main conclusions drawn from the above studies were related to the role of feed formulation and FCR as the predominant contributors to potential climate change and acidification impacts, followed by cage dimensions and fuel consumed by vessels operating on the farm. The rest of the available studies concerning gilthead seabream farming (García García *et al*., 2016; Abdou *et al*., 2017; Basto Silva *et al*., 2019), produced similar findings, while the environmental impacts of new fish species proposed for farming in the Mediterranean, including meagre, have never been assessed using LCA.

Given that Konstantinidis *et al*. (2020) showed that fish feeds had the most significant effect on the various environmental impact categories during the grow-out phase in two selected farms (in Greece and Albania, respectively), the present work focused in depth on feed manufacturing and the assessment of three pellet size classes routinely used during the on-growing cycle. Accordingly, the principal goals of this cradle-to-gate study were: a) to comparatively assess the impacts of feed and its granulation in particular (i.e. three pellet sizes), during the formulation process (including transportation) and shed light on the underlying factors affecting the predominant impact categories; and b) to compare the performance of seabass and meagre rearing, taking into account their commercial (i.e. at harvest) weight differences.

Material and Methods

Functional unit, system boundaries and LCA inventory

The functional unit (FU) of this study is defined as one tonne of harvested fish in isothermal bins transported to the packaging plant's gate for further packaging and was used as a reference unit for the quantification of all environmental impacts. This type of functional unit used to measure live-weight fish is the most commonly used in this type of studies (Henriksson *et al*., 2012; Cao *et al*., 2013).

The definition of system boundaries is critical for the assessment of environmental impacts associated with inputs and outputs, and the results of LCA are highly dependent on the product system defined (Mungkung & Gheewala, 2007). The system boundaries of this cradle-to-gate study were from fry stocking to the fish farm up to the output of one tonne of fish in isothermal bins, filled with ice and transported to the packaging plant's gate. During the fattening stage at the fish farms, feed, energy, fuel and water were needed (Fig.1, Table 1). Transportation of fry and aquafeed ingredients were not included in the calculations since they depend on availability and prices and, thus, country of origin/distance that influence transportation parameters. Aquafeed ingredients were taken into account from the entrance to the feeding plant.

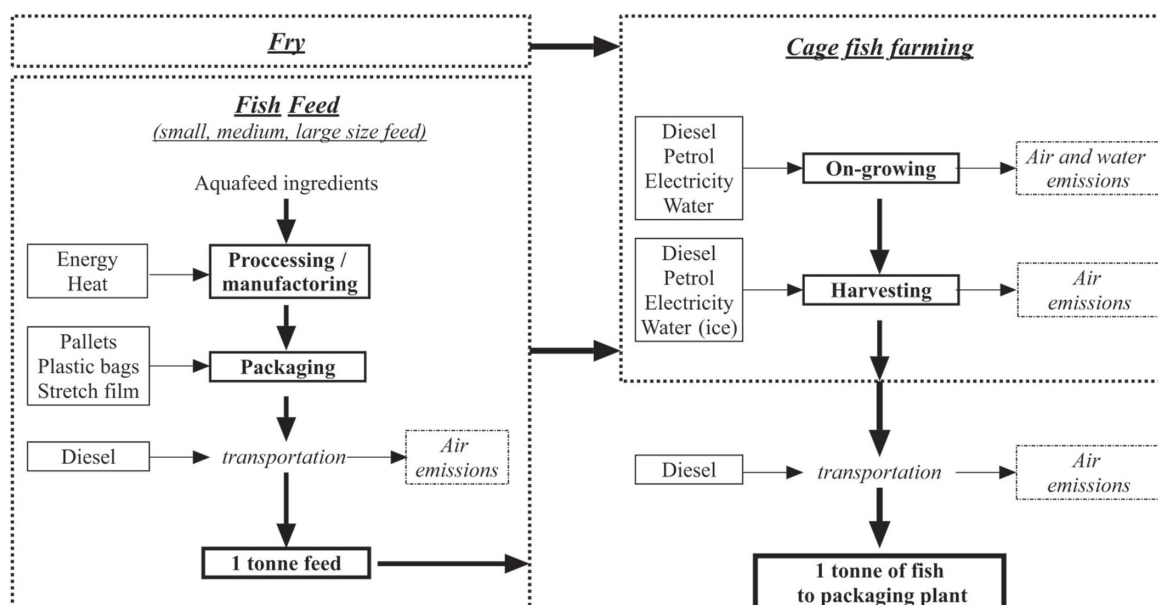In both sectors (feed plant and fish farms), as in most

Fig. 1: System boundaries.

Table 1. Amount of fuel, energy and water needed per FU.

	Diesel (l)	**Petrol** (l)	**Electricity** (KW)	**Water** (m³)
Seabass	47.07	21.65	47.66	0.278
Meagre	59.77	26.30	68.59	0.278

relevant LCA studies, infrastructure, capital goods and equipment such as cages and buildings, were excluded from the calculations (Mungkung & Gheewala, 2007; Roma *et al*., 2015), based on the lifespan of these facilities (i.e. long periods of amortization) (Ayer & Tyedmers, 2009; Iribarren *et al*., 2012). This assumption is usually made due to the fact that the environmental impacts involved, referring to the FU, can be neglected.

The selected impact assessment method was ReCiPe 2016 with 18 impact categories (Table 2).

Feeds

Raw data were acquired, following the ISO 14044 principles, from one feeding plant, located in the Peloponnese (southern Greece). Data were collected during 2016-2018, referring to a total annual quantity of 21,600 tonnes of aquaculture feed. Three types of fish feeds were assessed based on their initial ingredient composition and size (exact feed composition is available to the authors but not publically disclosed due to confidentiality reasons). The granulation of these types of feed ranged

Table 2. The 18 impact categories of mid-point Recipe 2016 (H).

Impact category	Symbol	Impact category	Symbol
Global warming	GW	Terrestrial ecotoxicity	TEx
Stratospheric ozone depletion	SozD	Freshwater ecotoxicity	Fex
Ionising radiation	Irad	Marine ecotoxicity	Mex
Ozone formation, human health	OzFHH	Human carcinogenic toxicity	HCTx
Fine particulate matter formation	FPMF	Human non-carcinogenic toxicity	HnCTx
Ozone formation, terrestrial ecosystems	OzFTE	Land use	LU
Terrestrial acidification	Tac	Mineral resource scarcity	MRSc
Freshwater eutrophication	Feu	Fossil resource scarcity	FRSc
Marine eutrophication	Meu	Water consumption	WC

from 0.3 to 2.5 mm (Small Sized Feed, SSF), 3.0 to 4.0 mm (Medium Sized Feed, MSF) and equal to or greater than 4.5 mm (Large Sized Feed, LSF). Within each feed size class (i.e. SSF, MSF and LSF), the composition was exactly the same (Table 3). For instance, fry need feed with pellet size from 0.3 to 2.5 mm, juveniles from 3.0 to 4.0 mm and adult fish need feed size equal to or greater than 4.5 mm. These three feed size classes have a different composition ("formulas"), including different amounts of fishmeal, fish oil, wheat, soy, vitamins, etc. All three different formulas were taken into consideration when conducting LCA. Moreover, the amount of energy consumed by the feeding plant was exclusively used to fulfil electricity (in KW) and heating (in Kg of propane) needs (Table 3).

Packaging material of feeds (i.e. wood for pallets, polyethylene for plastic bags and LDPE for stretching film), transportation (including atmospheric emissions due to fuel and maintenance oil) from the feeding plant to fish farms in Amvrakikos Gulf (263 km) and Sagiada Strip (390 km), were also taken into account for the calculations.

Fish farms

Raw data were acquired from four fish farms according to ISO 14044 principles with similar infrastructure and equipment levels. These sea cage farms are located in Sagiada Strip (Thesprotia) and in Amvrakikos Gulf (Preveza), western Greece, close to the shoreline (at a distance of 50-100 m). Data were collected during 2016-2018 and the total amount of harvested fish was 1,534.63 tonnes of seabass and 604.81 tonnes of meagre (Suppl. file on line, S1).

For the production of 1 tonne of commercial-sized product, the stocking of 2,868.7 seabass and 751.88 meagre fry individuals are required. The mean harvest size of farmed seabass was 0.437 kg, while the mean size for meagre was 2.142 kg. Seabass reached the above weight at 23.8 months and meagre at 32.8 months. During that period of time, the FCR value was 2.147 and 1.963 for seabass and meagre, excluding mortalities that reached 18.8% and 46.1%, respectively. Concerning the high mortality rate in meagre, this is mainly observed during the early stages of the on-growing phase and has a minor effect on the overall FCR value. Both species were fed on the same aforementioned types (i.e. pellet size classes) of

Table 3. Life cycle inventory of feed type per pellet size class in the feed production plant (for the production of 1 tonne feed).

	0.3 – 2.5 mm (small size feed)	3.0 – 4.0 mm (medium size feed)	≥ 4.5 mm (large size feed)
Fish meal	62.00	28.50	28.00
Fish oil	9.00	14.50	14.50
Vegetable origin (wheat meal, corn gluten meal, soy meal, sunflower meal, etc)	22.50	41.05	41.30
Amino acids (lycine, methionine)	1.10	1.90	1.00
Vitamins and minerals	1.40	1.05	1.10
Other (transformed animal proteins)	4.00	13.00	14.10
	100%	*100%*	*100%*
Packaging **EU pallet** (items)		*0.8*	
Plastic bags (kg)		*1.5*	
Stretch film (kg)		*4.0*	
Production capacity per hour (tn)	1.438	3.500	5.125
Electricity per tn (KWh)	152.24	62.53	42.7
Heat (kg propane)	237.75	97.64	66.86

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feed. Seabass were given 143.41 tonnes, 474.10 tonnes and 2,613.03 tonnes of SSF, MSF and LSF, respectively. For meagre, 21.21 tonnes, 40.93 tonnes and 1,121.40 tonnes of SSF, MSF and LSF were provided, respectively.

During the rearing stage, emissions of nitrogen (N) and phosphorus (P) due to feed metabolism (faeces, excretion), combined with N and P from uneaten feed and flesh retaining were taken into consideration and were related directly to the FCR value (Paspatis *et al.*, 2000; Karakassis *et al.*, 2005; Brigolin *et al.*, 2014). Moreover, fuel (diesel and petrol) is required for the boats/barges, for on-sea transportation and also for the forklift truck, passenger cars and trucks associated with the day-to-day operations of the farming units. As for all transportation, atmospheric emissions from fuels and oil used for maintenance were calculated. Finally, during harvesting, ice (water) is needed for filling the isothermal bins.

Calculation method

The midpoint ReCiPe 2016 (H) impact assessment/calculation method was selected because it is a problem-oriented method and allows identifying specific environmental hotspots during the production cycle. Moreover, this calculation method was chosen in order to avoid missing major impact parameters through grouping (i.e. end-point) (Huijbregts *et al.*, 2016). The contributional analysis (i.e. for comparison of the results) methodology was used, through normalization steps, in order to quantify the impact of the production system on the operation of the feeding plant. All midpoint impacts in this study were normalized according to the global normalization factor for year 2010. Finally, concerning climate change (i.e.

impact category "global warming"), the midpoint method refers to a 100-year timeframe, as this is the basis adopted by the Kyoto Protocol I (EC-JRC, 2011). All calculations were performed with the SimaPro software package, ver. 9.0 (PRé Sustainability BV, Netherlands) using the Eco-Invent® (ver. 3.5; Wernet *et al.*, 2016) and Agribalyse® (ver. 1.3; Koch & Salou, 2016) databases.

Results

Feeds

Calculations for each feed were made in order to identify the main factors contributing to environmental impacts, depending on their size. Using the characterization calculation method, the worst impact scores 100% per impact category and all other impacts are expressed as a relation to that. For eight impact categories, SSF scored lower, followed by LSF in seven categories. For most of them, environmental performance of MSF was between SSF and LSF. In particular, SSF scored lower than the MSF and the LSF regarding "global warming" (up to 20.0%), "stratospheric ozone depletion" (up to 29.4%), "terrestrial acidification" (up to 12.8%), "land use" (up to 46.2%), "mineral resource scarcity" (up to 39.4%), "water consumption" (up to 2.3%), (SSF<MSF<LSF). However, LSF performed better compared to MSF (SSF<LSF<MSF) for "marine eutrophication" (up to 21.1%) and "freshwater ecotoxicity" (up to 57.6%) (Fig. 2).

In three impact categories, MSF scored lower compared to the rest of the feed sizes (MSF<LSF<SSF), namely, "ionizing radiation" (up to 8.2%), "ozone formation human health" (up to 15.6%) and "ozone formation,
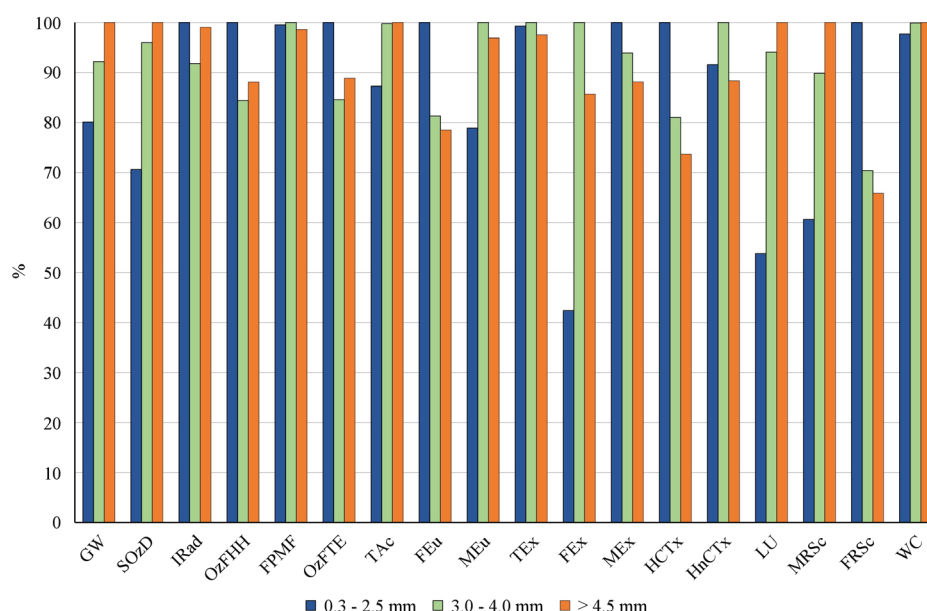

Fig. 2: Comparison of different feed types (i.e. pellet size classes) (characterization). GW: Global warming, SozD: Stratospheric ozone depletion, Irad: Ionising radiation, OzFHH: Ozone formation, human health, FPMF: Fine particulate matter formation, OzFTE: Ozone formation, terrestrial ecosystems, Tac: Terrestrial acidification, Feu: Freshwater eutrophication, Meu: Marine eutrophication, TEx: Terrestrial ecotoxicity, Fex: Freshwater ecotoxicity, Mex: Marine ecotoxicity, HCTx: Human carcinogenic toxicity, HnCTx: Human non-carcinogenic toxicity, LU: Land use, MRSc: Mineral resource scarcity, FRSc: Fossil resource scarcity, WC: Water consumption.

terrestrial ecosystems" (up to 15.5%) (Fig. 2).

Concerning LSF, lower scores (LSF<SSF<MSF) were documented in impact categories "fine particulate matter formation" (up to 1.4%), "terrestrial ecotoxicity" (up to 2.5%), "human non-carcinogenic toxicity" (up to 11.7%) and also in (LSF<MSF<SSF) "freshwater eutrophication" (up to 21.5%), "marine ecotoxicity" (up to 12.0%), "human carcinogenic toxicity" (up to 26.3%) and "fossil resource scarcity" (up to 34.1%) (Fig. 2).

In order to identify major categories affected by aquafeeds, the normalization method was applied. Based on

the normalization results, feed production mostly affected the impact categories "freshwater ecotoxicity" and "marine ecotoxicity", followed by "human carcinogenic" and "non-carcinogenic toxicity" (Fig. 3).

In the SSF class, electricity (KW/tn feed) was the predominant (40.1%) factor in the "freshwater ecotoxicity" impact category, while fishmeal (28.5%) and electricity (33.9%) were the predominant contributing factors in the "marine ecotoxicity" impact category (Fig. 4). On the other hand, sunflower meal contributed most to the "freshwater ecotoxicity" impact category, both in the MSF and
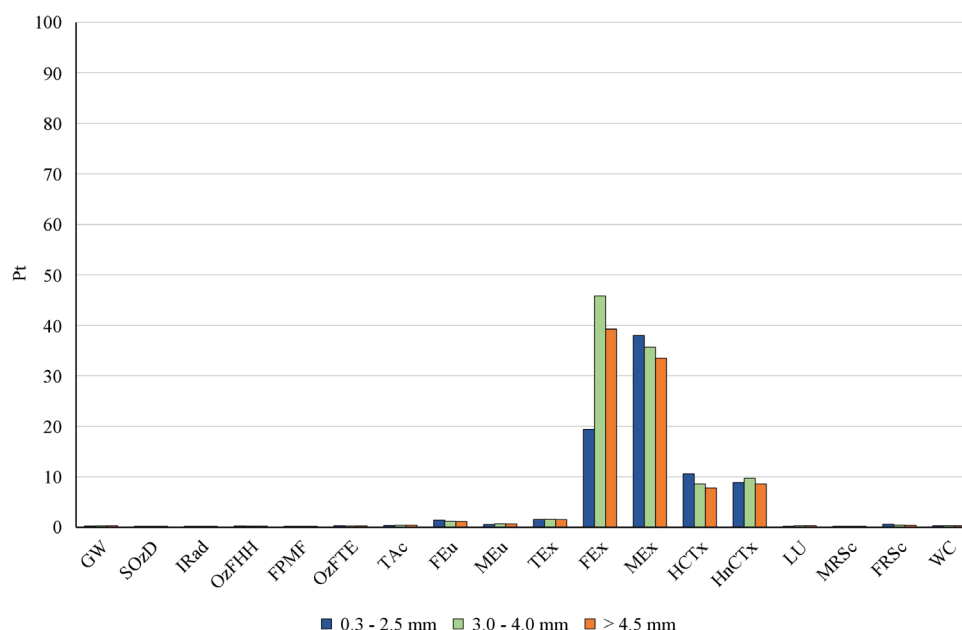

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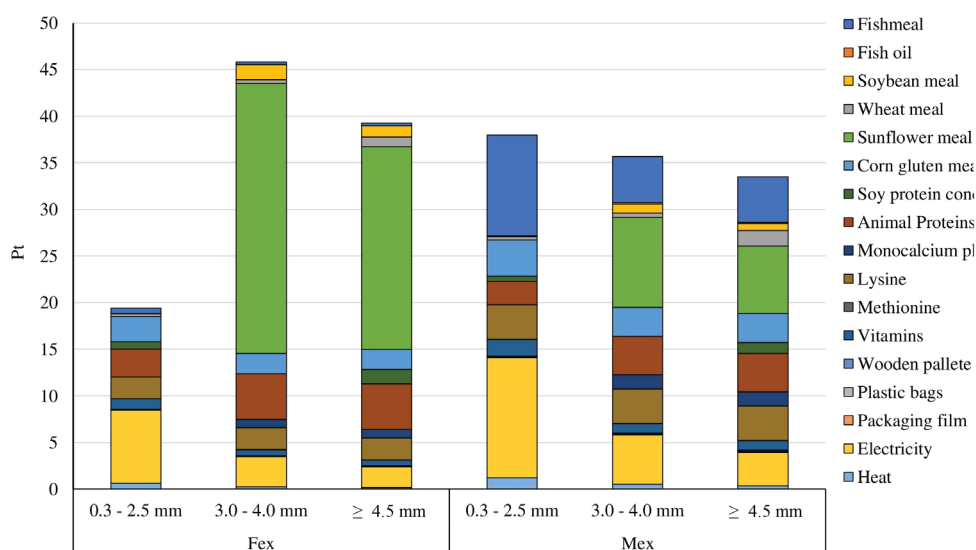

Fig. 4: Percentage contribution of feed ingredients and other resources and materials to "freshwater ecotoxicity" (Fex) (in kg 1.4DCB-eq) and to "marine ecotoxicity" (Mex) (in kg 1.4DCB-eq), in three different feed size (pellet) classes.

LSF classes (63.2% and 55.4%, respectively). Similarly, sunflower meal contributed most to the MSF and LSF classes (27.0% and 21.6%, respectively), regarding the impact category "marine ecotoxicity" (Fig. 4).

Fattening

Calculations were made for each fish species using the characterization method in order to identify the main factors contributing to environmental impacts. LSF consumption was the prominent factor, affecting almost all environmental indicators in both species, with minor differences between them (Fig. 5a, b). Only impact category "water consumption" was affected to a higher degree by fry production, in both species. More specifically, in seabass, fry production affected impact categories "water consumption" by 85.4% and "ionizing radiation" by 53.2%. In addition, MSF affected 16 impact categories, from 11.8% to 16.8%, and SSF up to 5.5% in all categories. Similarly, in meagre, fry production affected impact categories "water consumption" by 66.2% and "ionizing radiation" by 27.3%. MSF affected 17 (out of 18) impact categories by 2.3% - 4.0% and SSF up to 2.3% in all impact categories.

Following feed size assessment and having in mind the significant amount of feed consumption needed per FU, a direct comparison of seabass and meagre hotspot analysis, showed that meagre scored lower (from 6.9% to 60.3%, with a mean reduction of 14.6%) than seabass in all environmental impact categories (Fig. 6). The highest difference was evident in "water consumption" (60.3%) and in "ionizing radiation" (40.6%) due to the different amount of fry required for each species. Concerning "global warming" the difference was lower by 8.4% in meagre.

Discussion

Assessment of aquaculture's environmental performance is a difficult task because activities and potential impacts vary. However, there is an increasing emphasis on using more holistic analysis to compare the overall impact of different agricultural production systems for the assessment of environmental impacts and resource use in a production process and to identify opportunities for increasing resource use efficiency. The challenge, therefore, is to satisfy the growing demand while reducing and mitigating environmental impacts (Besson *et al.*, 2017). LCA is the most widely used method to quantify the environmental impacts of a production system on a global scale (Bohnes & Laurent, 2019).

The LCA comparison between three different pellet sizes, revealed that the SSF performed better compared to MSF and LSF, for various environmental impact indicators (i.e. "global warming", "stratospheric ozone depletion", "terrestrial acidification", "marine eutrophication", "freshwater ecotoxicity", "land use", "mineral resource scarcity" and "water consumption"). This does not imply that ingredients/formula and the formulation process in the starter feed have a more overall eco-friendly profile. In fact, fish meal, energy and heat requirements per tonne of feed production were 34%, 356% and 355% higher, respectively, compared to the lower requirements of larger pellet sizes. Moreover, the SSF displayed inferior environmental performance in other impact categories such as "ozone formation human health", "ozone formation, terrestrial ecosystems", "freshwater eutrophication", "human carcinogenic toxicity" and "fossil resource scarcity", suggesting that certain aspects of resource use and processing contribute environmental burdens to the feed formulation process.

Based on the normalization LCA assessment process, it was evident that feed production mostly affected the
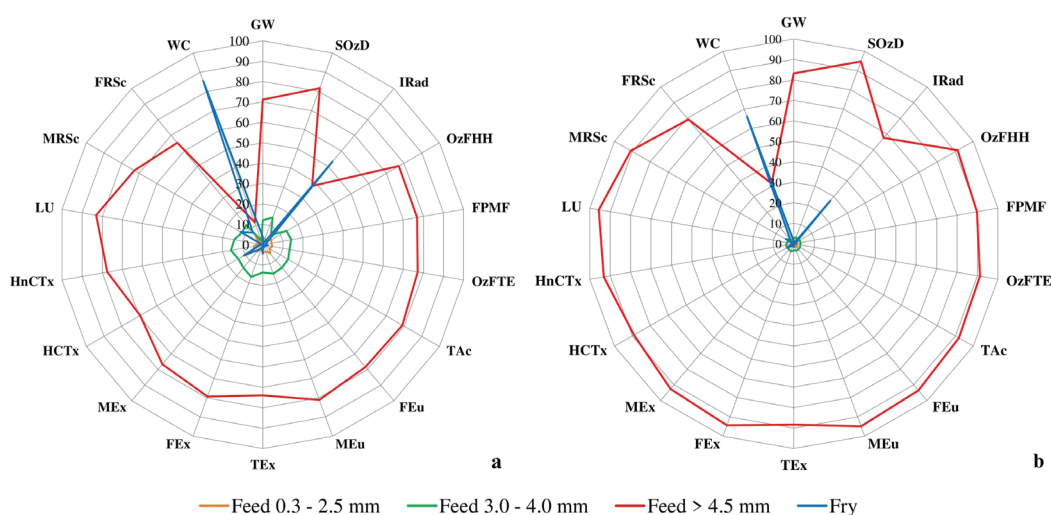

—— Feed 0.3 - 2.5 mm —— Feed 3.0 - 4.0 mm —— Feed > 4.5 mm —— Fry

Fig. 5: Major environmental impacts in farmed (a) seabass and (b) meagre during cage farming (characterization). GW: Global warming, SozD: Stratospheric ozone depletion, Irad: Ionising radiation, OzFHH: Ozone formation, human health, FPMF: Fine particulate matter formation, OzFTE: Ozone formation, terrestrial ecosystems, Tac: Terrestrial acidification, Feu: Freshwater eutrophication, Meu: Marine eutrophication, TEx: Terrestrial ecotoxicity, Fex: Freshwater ecotoxicity, Mex: Marine ecotoxicity, HCTx: Human carcinogenic toxicity, HnCTx: Human non-carcinogenic toxicity, LU: Land use, MRSc: Mineral resource scarcity, FRSc: Fossil resource scarity, WC: Water consumption.

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Fig. 6: Comparison of impacts on environmental indicators in seabass and meagre (characterization). GW: Global warming, SozD: Stratospheric ozone depletion, Irad: Ionising radiation, OzFHH: Ozone formation, human health, FPMF: Fine particulate matter formation, OzFTE: Ozone formation, terrestrial ecosystems, Tac: Terrestrial acidification, Feu: Freshwater eutrophication, Meu: Marine eutrophication, TEx: Terrestrial ecotoxicity, Fex: Freshwater ecotoxicity, Mex: Marine ecotoxicity, HCTx: Human carcinogenic toxicity, HnCTx: Human non-carcinogenic toxicity, LU: Land use, MRSc: Mineral resource scarcity, FRSc: Fossil resource scarity, WC: Water consumption.
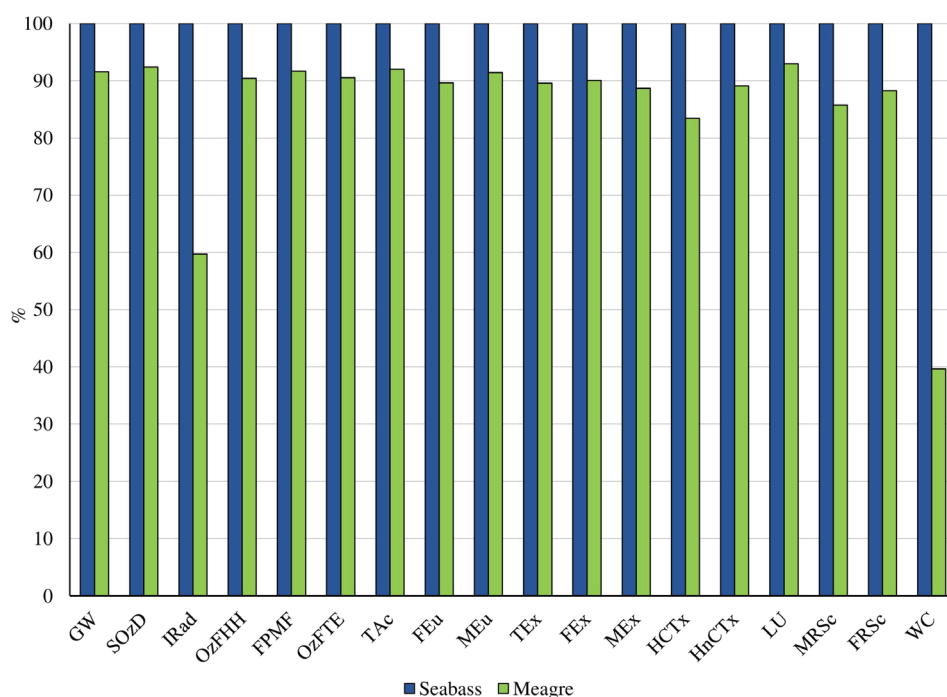
"freshwater ecotoxicity" and "marine ecotoxicity" impact categories. Concerning the "freshwater ecotoxicity" impact category, MSF and LSF were mostly affected by sunflower meal. Sunflower meal has been used as a substitute for fish meal with good results as regards substitution (up to 30%) (Olim, 2012). The negative impact of sunflower meal was mainly due to the use of *Chorpyrifos*, an aerial-sprayed chlorinated organophosphate pesticide that is widely used for the control of soil-born insects (US-EPA, 2002; Ali *et al*., 2009). Moreover, during sunflower cultivation, the use of significant amount of fertilizers such as boric acid and especially phosphate, which are rich in heavy metals such as nickel, copper and manganese, contributes negatively, through emissions, to the "freshwater ecotoxicity" category (Matsuura *et al*., 2017). Finally, this impact category was affected by the use of animal proteins. More specifically, it was impacted by animal feeds containing sunflower meal and lysine, an essential amino acid used for the biosynthesis of proteins that can be obtained from livestock and a variety of crop plants (particularly cereals and legumes) (Galili & Amir, 2013). On the contrary, the "freshwater ecotoxicity" category in SSF class, which does not include sunflower meal, was mostly affected by electricity. This is because Greece's energy mix relies on lignite/coal for electricity production (29.5%) (Angelopoulos *et al*., 2017), which in turn produces negative environmental impacts.

Contrary to the previous pattern, SSF displayed the greatest environmental impact on "marine ecotoxicity", mainly due to the lower production capacity per hour of the feeding plant (i.e. 1.438 t/h compared to 3.500

t/h and 5.125 t/h for MSF and LSF, respectively). This category was predominantly affected by electricity due to the aforementioned reasons (i.e. production capacity and Greece's energy mix) and secondarily fishmeal. The higher contribution of fishmeal compared to MSF and LSF, was due to the larger amount required in the formula (62.0% vs 28.5% & 28.0%). Given that, under conditions of intense industrial exploitation, climatic oscillations may push stocks destined for fishmeal/fish oil production beyond their replacement rate, the use of fishmeal raises concerns about the sustainability of aquaculture and its resilience to climate change (Naylor & Marshall, 2005; Beveridge *et al*., 2018). Although the inclusion of sunflower meal produced the predominant impact, the inclusion of fishmeal affected the performance of MSF and LSF (in relation to the "marine ecotoxicity" category).

The assessment of the farming cycle in both species showed that the LSF class affected, to various degrees, almost all environmental impact categories. This was expected given that the amount of feeds produced and distributed to the farmed stocks during the on-growing stage is huge, compared to the rest of the feed size classes. In fact, the LSF class accounts for 80% in seabass and 94% in meagre of overall feed consumption. This is in line with relevant studies on other farmed species such as salmon (Ellingsen & Aanondsen, 2006; Pelletier *et al*., 2009). Finally, the "water consumption" impact category was primarily affected by fry production, due to the vast water requirements of hatcheries.

Overall, the comparison between seabass and meagre rearing revealed that meagre, although harvested at

a much bigger (commercial) size compared to seabass, displayed a significantly lower impact for all eighteen environmental impact indicators considered. This should be attributed to the fact that: a) meagre is a better food converter than seabass, based on the relevant mean FCR values, which is reflected in the lower demand for feed for the production of 1 tonne of harvested fish; and b) the production of one tonne of meagre requires almost 4 times fewer fry individuals (including mortalities), compared to seabass, which means that the water requirements are higher. Accordingly, the overall impacts of meagre farming compared to seabass farming, based on the total production per species in Greece (i.e. 2,000 tonnes vs 55,200 tonnes; FGM, 2020) are much lower than their actual relative percentage contribution to marine fish farming production.

According to Waite *et al*. (2014), if aquaculture is to double its production by 2030 and in order for this growth to be sustainable, the sector must improve its productivity, without compromising environmental performance (Lotze *et al*., 2019). Further research on fishmeal and fish oil substitution is imperative. Available options leading to 60-75% reduction of dietary fishmeal and fish oil for the majority of farmed fish species is biologically feasible; these options could be based on alternative lipid sources, without significantly affecting growth performance, feed efficiency and feed intake (Turchini *et al*., 2009). Raw materials such as soya, corn, wheat and sunflower, provide proteins and oils that have been largely introduced in fish diet formulation (Glencross *et al*., 2007; Sales, 2009). The high prices of fishmeal and fish oil are forcing feed manufacturers to reduce the amounts of fish-based ingredients in favour of oilseeds and meal from plant material and to search for cheaper, alternative sources, such as fish processing wastes (Little *et al*., 2016), single cell proteins and yeasts. Therefore, the aquafeed industry is bound to seek alternative dietary proteins and lipid sources. However, shifting to alternative raw materials will need to be thoroughly studied and optimized to ensure that these raw materials are more sustainable than the currently used ones. Terrestrial raw materials have totally different impacts than those of marine origin and should be evaluated in detail aiming at the formulation of more eco-friendly fish feeds.

This work documented the usefulness of the LCA method of environmental management in seabass and meagre farming. Although it is not the 'silver bullet' for any problem, it does provide valuable information that can be used as a basis for decision-making and the adoption of policy measures to assess the environmental performance of production processes and mitigate any problems caused to the natural environment.

The application of LCA to three different feed size classes revealed that SSF pellets had a lower impact on many environmental indicators, followed by the LSF and the MSF size classes. The assessment demonstrated that the greatest environmental impact was evident for the "freshwater ecotoxicity" and "marine ecotoxicity" categories and sunflower was the predominant factor, followed by electricity consumption and fishmeal in-clusion. Meagre cage farming, displayed better overall environmental performance, compared to seabass. The differences should be attributed to the FCR value and the amount of fry required for the entire production cycle. The results are in line, from another standpoint, with relevant research showing the prospects of meagre farming due to good adaptability to captivity, impressive growth rate, flesh quality, low FCR ratio, excellent marketing potential and higher commercial price (Soares *et al*., 2015). Moreover, added-value products can be produced from meagre, such as fillet and fresh or frozen portions (Saavedra *et al*., 2015). Given that feed formulation, feeding management and eventually FCR are the most crucial factors defining the environmental performance of Mediterranean fish farms (e.g. Tunisia: Abdou *et al*., 2017; Greece and Albania: Konstantinidis *et al*., 2020), attention should be paid to improve the cultivation and processing methods of raw materials and especially seeds, through better procurement practices and eco-labelling. Nutritionally balanced fish feeds with optimized inclusion of raw materials of marine origin would contribute to the economic performance of the fish farming industry with possible positive effects on the overall ecological sustainability of final products.

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Supplementary data

The following supplementary information is available online for the article:
Table S1. Raw data from seabass and meagre fish farms (mean weights and FCRs are weighted averages).

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