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Environmental sustainability of future aquaculture production: Analysis of Singaporean and Norwegian policies

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ABSTRACT

To address global food demand and sustainability challenges, aquaculture has appeared as an essential element in food systems, and an increasing number of national aquaculture policies have emerged over the past decades. However, several of these policies have failed because of an often-argued inability to anticipate their far-reaching implications on environmental and socio-economic variables. To tackle this gap, we propose a step-wise framework to assess the national environmental impacts from aquaculture industries with a prospective and systemic approach. Starting from identifying policy-based national targets, the methodology relies on economic equilibrium modeling to develop realistic future-oriented scenarios of the aquaculture sector, and couples them with life cycle assessment principles. To evidence its operability, we apply the framework to two distinct case countries: Norway and Singapore. Beyond our key findings from the analyses of the policies in both countries, we observed that feed production and usage are important drivers of impacts, hence calling for new and more environmentally-friendly feed options. Our results additionally show that the development of aquaculture following existing governmental policies may not directly reduce greenhouse gases emissions and, hence, not support climate change mitigation objectives. These findings should however be cautioned as potential shifts of diets due to the increasing seafood availability might occur, leading to indirect environmental benefits. We therefore advocate the further expansion of our framework to cover the entire food system, so it can integrate such indirect effects. Meanwhile, we recommend its interim application to support policy-making and help move towards more environmentally sustainable aquaculture systems.

1. Introduction

World aquaculture production has increased from ca. 10 million tons of live-weight seafood in 1990 to more than 80 million tons in 2016 (FAO, 2018). This escalation, which addressed the increase of global food demand due to a growing global population and an increasing average revenue per capita, is expected to continue, albeit at a lower growth rate (FAO, 2018). Aquaculture is therefore a key feature of food security and local economies, in addition to contributing to the availability of healthy diets resulting from the high content in seafood of healthy long-chain fatty acids, proteins, vitamins, and minerals (Larsen et al., 2011). It is therefore not surprising to find seafood as part of the sustainable diet established by the EAT-Lancet Commission (2019). This makes its production appealing for low- as well as high-income countries (FAO, 2011). However, major aquaculture growth has in general been limited to low- and middle-income countries, and despite multiple attempts to implement policies aimed at boosting it, with a few exceptions, high-income countries have overall faced difficulties to trigger their aquaculture revolution (Abate et al., 2016; Anderson et al., 2019; Costa-Pierce, 2010; FAO, 2016; Garlock et al., 2020).

Studies have shown that countries with strict environmental regulations, like most high-income countries, often experienced delayed growth of their aquaculture sector because of a lack of technically viable solutions for more environmental-friendly aquaculture technologies and the lack of quantitative assessments providing proofs of the environmental benefits of such technologies (Abate et al., 2018; Abate et al.,

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2016). Environmental regulations are necessary for preserving biodiversity because, despite its indisputable socio-economic advantages, aquaculture production has been found to have various negative impacts on the environment (see e.g. Gausen and Moen, 1991; Jayanthi et al., 2018; Ottinger et al., 2016). It affects local ecosystems, for example due to nutrients emissions in surrounding waters or interactions with local environments, and contributes to global environmental problems such as climate change and fish stock depletion, through its usage of fishmeal and fish oil (FMFO) in the feed (Diana, 2009; Naylor et al., 2000). Environmental implications of new policies should therefore be assessed and put in perspective with existing environmental regulations beforehand (Hall et al., 2011). Furthermore, as environmental impacts of aquaculture highly depend on the technologies used (Bohnes et al., 2019), assessment of the environmental impacts of new policies should be based on potential future scenarios of aquaculture development that the said policies would imply in terms of technology change and implementation.

Life cycle assessment (LCA) has been extensively used to quantify environmental sustainability of aquaculture systems through assessments of a large set of environmental impact categories (Bohnes et al., 2019). This ISO-standardized methodology can be used to compare different aquaculture systems and identify environmental hotspots of aquaculture technologies through their whole life cycle, i.e. from raw material extraction to end-of-life, including production, transport and consumption of seafood (ISO, 2006a, 2006b). LCAs of seafood products have become increasingly popular and necessary, as illustrated by the ongoing development of the product environmental footprint and category rules for marine fish at European level (Hognes, 2014). Multiple LCA studies can be found for individual farms, capturing existing commercial ones as well as pilot projects. However, sector-wide LCA studies have been rare for aquaculture until now, and they have typically been limited to specific species, e.g. assessment of the current impacts of the mussel production sector in Spain by Iribarren et al. (2010). Two noticeable exceptions are Henriksson et al. (2017), who adopted a sectorial perspective to assess the environmental impacts of the entire Indonesian aquaculture sector (i.e. a low-income country) until 2030; and Bohnes and Laurent (2021), who assessed the environmental impacts of various farming techniques in Singapore for the years 2016 and 2040. They were the only ones to take a prospective angle, but the latter limits its assessment to the farm level and the former is case-specific, with no framework developed to generalize the application of such approach. In addition to environmental sustainability, social and economic sustainability dimensions should also be addressed, and assessment frameworks and methods may be applied to assess them (albeit with a need for method development), e.g. the UN Sustainable Development Goals framework and its proposed indicator sets, social LCA, etc. In this study, the focus is however centered on addressing environmental sustainability, which is essential to sustain socio-economic systems (Griggs et al., 2013). In this paper, we aim to develop a framework for prospective and systemic assessment of environmental impacts from aquaculture industries at national level based on the comparison of policy-based scenarios. As a proof-of-concept, the framework is applied to two case countries: Norway and Singapore. These countries were chosen because they are both high-income countries with ambitious aquaculture development policies, although with very different production landscapes in terms of species, environmental conditions and technologies, and because they represent the important difference between cold-water and warm-water aquaculture systems. The framework's results, such as the recommendations to policy-makers, therefore cannot be directly compared between the two countries, but the feasibility of the framework can be illustrated and parallels can be drawn based on the types of conclusions that both case studies will generate. In following Section 2, the framework is introduced and its main features described, along with documentation of the two case studies of Norway and Singapore. The assessment results are discussed in detail for each country in Sections 3 and 4, eventually leading to a more general discussion of the framework, including its operability and its limitations in Section 5.

2. Material and methods

2.1. Overview of the framework

The proposed framework builds on the general LCA framework, as defined by the ISO 14040:2006 and 14044:2006 standards, and offers a structure to harmonize large-scale, prospective LCAs of the aquaculture sector. It contains 4 main steps illustrated in Fig. 1. Prior to Step 1, the object of the assessment is defined as the country under study, the policy to be assessed and the period over which the assessment is conducted. The framework can also focus on other geographical scales than the country level, e.g. aquaculture sector at regional (European Union) or state (e.g. Mississippi, US) levels. In Step 1, the current aquaculture industry of the targeted country is described in detail, i.e. which species are produced and with which technologies. Indeed, aquaculture gathers a large variety of species, including different taxonomic groups (e.g. fish, mollusks, crustaceans, plants, algae), which require substantially different technologies to be farmed due to the different natural requirements for their growth. As the environmental impacts of seafood production highly depend on the specific technologies used, these should be described as precisely as possible and classified by type to allow a meaningful assessment of the environmental impacts. To that purpose, production categories should be formed by associating species and technologies that have similar production processes, and therefore having the same type of inputs, outputs and emissions at the production level and are likely to be similar in terms of environmental impacts. Additionally, literature should be reviewed and experts consulted to identify potential new species and technologies that are likely to enter the countries' aquaculture landscape within the assessed period. Then, we propose an optional Step O that consists of a micro-scale LCA, in which the impacts per ton of edible seafood of the production categories identified in Step 1 are compared. This step is recommended when the environmental impacts of aquaculture in the country or geographical area considered have rarely been assessed before, and that estimating them for the different production categories would therefore be unreasonable or even biased (due to e.g. popular belief or comparison to technologies that seem similar but could potentially be associated to divergent impacts). Additionally, it would contribute to building a broader knowledge regarding the environmental impacts associated to aquaculture in different regions and climates, and for different species, which might help the understanding of the main environmental challenges linked to this industry. It is however not necessary in the case of countries that have been extensively assessed in past LCA studies on aquaculture (e.g. Norway).

Step 2 aims to build scenarios of potential aquaculture development based on the specific socio-economic context of the country. These scenarios should describe the evolution of the production quantities of each category of species-technology identified previously through the identified period. We recommend for this step the use of equilibrium supply-demand economic models, such as Asiafish (developed by Worldfish - Dey et al., 2005), which enable to consider the consumption, factoring in imports and exports, as well as the production. Such models have been developed by Tran et al. (2017) and Bohnes et al. (2020), who extensively documented the modeling background. Their application of equilibrium economic models to the two cases of Singapore and Norway is detailed in Sections 2.2.1 and 2.2.2, respectively. So far, such models do not contain a comprehensive environmental impact assessment module.

Therefore, Step 3 consists of generating the evolutions of the average environmental impacts of seafood production in the country per ton of edible product in the different scenarios. To that purpose, a life cycle assessment of the national aquaculture industry is conducted (i.e. large-scale). First, life cycle inventories (LCI) of the different production

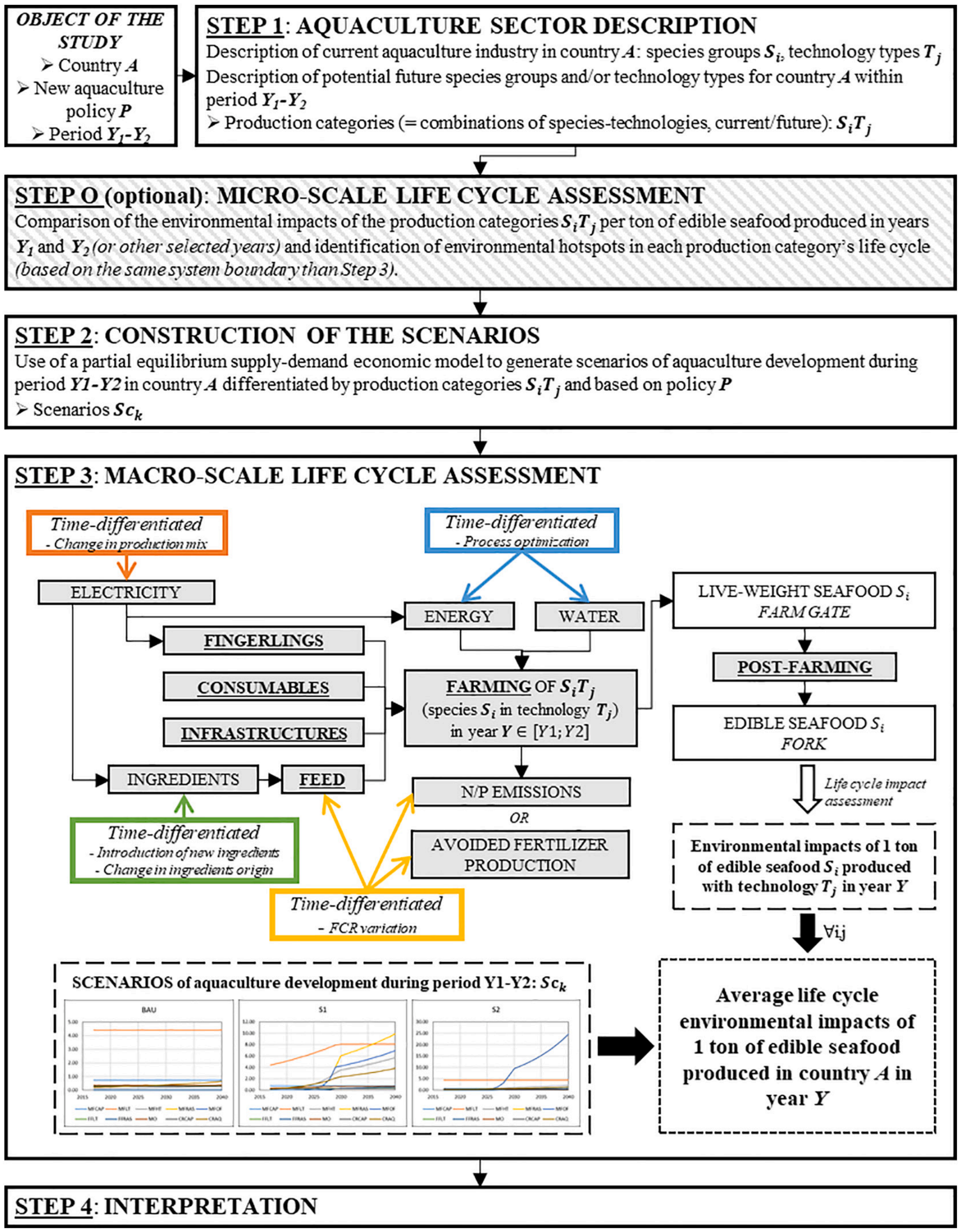

Fig. 1. General methodological framework of the study. Grey boxes are processes that need to be aggregated to be representative of the country's average processes.

categories need to be built, including the modeling of their evolution through the considered reference time period. All relevant production elements need to be included (i.e. production, feed, infrastructures, consumables and post-farming – see Fig. 1). Data should be compiled for the country-representative processes and also include time differentiation features to reflect potential technology optimization and expected changes in farmers' habits along the period, including feed selection (Fig. 1). An extensive set of environmental impact categories should be assessed, including toxicity impacts, resource use impacts and biomass extraction as recommended in Bohnes and Laurent (2019). Finally, in Step 4, the results of the LCA are interpreted considering the limitations and uncertainty of the study.

All steps applied to the case studies are described in the following sections. Steps 1 and 2 are addressed in Section 2.2, Step 3 in Section 2.3, while the results and interpretation (Step 4) are the focus of Sections 3 and 4 for Singapore and Norway, respectively.

2.2. Introduction to the case studies

In Sections 2.2.1 and 2.2.2, Steps 1 and 2 are applied to the two case studies: Singapore and Norway.

2.2.1. Singapore in the quest for higher self-sufficiency

Singapore currently has a modest food industry, with only 10% of its consumption covered by domestic production (SFA, 2019). The Singaporean government recently announced a new food policy named the

Table 1
Description of the current and future aquaculture systems in Singapore with abbreviations, differentiation between juveniles and grow-out when needed, feed type, and whether it is a closed or open system. Future technologies are indicated with an "*" symbol.

Species group	Technology type	Category abbreviation	Juveniles growth	Grow-out system	Feed	Open /closed
Marine fishes	"Low-tech"	MF-LT	Fiberglass tanks equipped with flow-through water system	Sea nets attached to floating platforms made of wood and plastic.	Dry pellets	Open
	"High-tech"	MF-HT	Fiberglass tanks equipped with optimized water recirculating system (RAS).	Large cages in the sea built close to the shore.	Dry pellets	Open
	RAS*	MF-RAS*	Fiberglass tanks equipped with highly optimized water recirculating system.		Dry pellets	Closed
	Offshore*	MF-OF*	Fiberglass tanks equipped with optimized water recirculating system (RAS).	Large cages in the sea built far from the shore.	Dry pellets	Open
Freshwater fishes	"Low-tech"	FF-LT	Fiberglass tanks equipped with flow-through water system.	Concrete ponds dig in the ground with flow-through water system.	Industry by-products	Closed
	RAS*	FF-RAS*	Fiberglass tanks equipped with highly optimized water recirculating system.		Dry pellets	Closed
Mollusks	"Low-tech"	MO-LT	Long lines and plastic barrels attached to floating platforms made of wood and plastic.		Unfed	Open
Crustaceans	"High-tech"	CR-HT	Individual plastic boxes equipped with highly optimized water recirculating system.		Fresh seafood	Closed

"30-by-30", which aims at increasing to 30% the proportion of its consumption provided by domestic production by 2030. A case study is therefore defined to analyze the implications of this policy, assuming the same objectives to the seafood sector during and post-implementation, hence the choice of 2017–2040 as the reference period.

Four species groups (marine fishes, freshwater fishes, crustaceans and mollusks) and two technology types ("low-tech" and "high-tech") were identified in Singapore, and classified into 5 production categories (see definition in Section 2.1). Additionally, we identified two potential future technologies to be implemented in Singapore: recirculating aquaculture systems (RAS) and offshore aquaculture, that would be used for fishes essentially. All production categories are described in detail in Table 1. Additionally, we decided to assess two different Feed options that reflect two strategies: (1) an increased proportion of trimmings in FMFO manufacturing, and (2) an increased proportion of soybean meal accompanied with the introduction of insect-based meal and algal oil to replace FMFO. More details about the choice of the different technologies and feed options are available in Bohnes and Laurent (2021), which provide detailed LCIs and associated assessment at farm level of several farming techniques in Singapore for the years 2016 and 2040 (optional Step O in the framework).

Reflecting the Singaporean government's ambition to increase aquaculture production before 2030 through its new policy, we built three scenarios of aquaculture development in Singapore for 2017–2040. The detailed method for the development and construction of the scenarios from an economic perspective is available in Bohnes et al. (2020). The first scenario is a "Business-as-usual" situation, where the different production categories follow historic trends to increase slowly (SG-BAU). With this scenario, the goal of the Singaporean government regarding 30% self-sufficiency is not reached in 2030. The two other scenarios developed are explorative ones, where the different categories undertake different growth rates to fulfill the objective of 30% of seafood self-sufficiency by 2030. While all production categories increase in scenario 1 (SG-S1), scenario 2 (SG-S2) focuses on future technologies (Fig. 2).

2.2.2. *Norway in the reign of salmon*

Norway is a strong actor in seafood production globally, and the Norwegian government intends to maintain this status with a continually growing seafood sector. In that context, authorities are determined to keep their position as the world leader in salmon production, yet within a sustainable framework (Norwegian Minitries, 2019). Under these circumstances and since 2005, the Norwegian government has introduced licenses and a traffic light system with production thresholds, aiming at maintaining salmon production to sustainable levels (Hersoug, 2021; Hersoug et al., 2021). However, the salmon industry currently faces several challenges and its growth is deemed compromised if solutions are not implemented to address them (Lekang et al., 2016). The control of diseases, in particular sea lice, and escapes from farms are currently the main issues (Lekang et al., 2016). To tackle them, the Norwegian government has drafted two complementary pathways: facilitating the sustainable development of new technologies that would solve these problems, and diversifying aquaculture production by introducing other species than salmon and trout (Norwegian Ministry of Fisheries and Coastal Affairs, 2009; Norwegian Minitries, 2019). The case study aims at assessing the environmental impacts of these two approaches of the Norwegian government.

Norwegian aquaculture is limited to a few species and consists of almost 95% of Atlantic salmon, for which Norway is the production and export world leader (FAOSTAT, 2019). Norway has optimized its production over decades, usually growing the juveniles in closed tanks on land equipped with recirculating water systems and fully controlled ambient parameters before transferring the fishes in sea cages for the grow-out phase (Lekang, 2007). In recent years, the production of white fishes such as cod began to develop using this same technology (Rosenlund and Halldórsson, 2007). Additionally, salmons and mollusks in integrated multi-trophic aquaculture (IMTA) is another innovative technology that is advocated by researchers to be developed in the future in Norway. It is an aquaculture technique where several species from different trophic levels are grown in close proximity in order to optimize the use of nutrients and therefore reduce the cost of production by reducing the feed need (Wang et al., 2012). An analysis of the literature revealed that full RAS and offshore aquaculture have a potential for development in the future for salmonids, similarly to marine fishes in Singapore (Dalsgaard et al., 2013; The Research Council of Norway, 2005). All production categories are described in Table 2.

The same two feed options as for Singapore will be assessed for Norway, i.e. (i) higher proportion of FMFO produced through trimmings and (ii) replacement of FMFO by insect-based meal and algal oil.

Based on the incentive scheme of the Norwegian government, we developed three scenarios of aquaculture development for Norway over, 2017–2040. Their construction and details about the obtained imports, exports, consumption and production of the different production categories are available in Supplementary Methods. The first scenario describes a business-as-usual situation (NO-BAU), with only a historical increase in salmonids production in sea cages. Scenario 1 (NO-S1) illustrates an important increase in the production of salmonids due to a quick reduction of environmental issues and a diversification of technologies. Scenario 2 (NO-S2) portrays species diversification and limited increase of the production of salmonids in sea cages due to a slow reduction of environmental issues. However, none of the obtained scenarios allows a true diversification of the Norwegian aquaculture

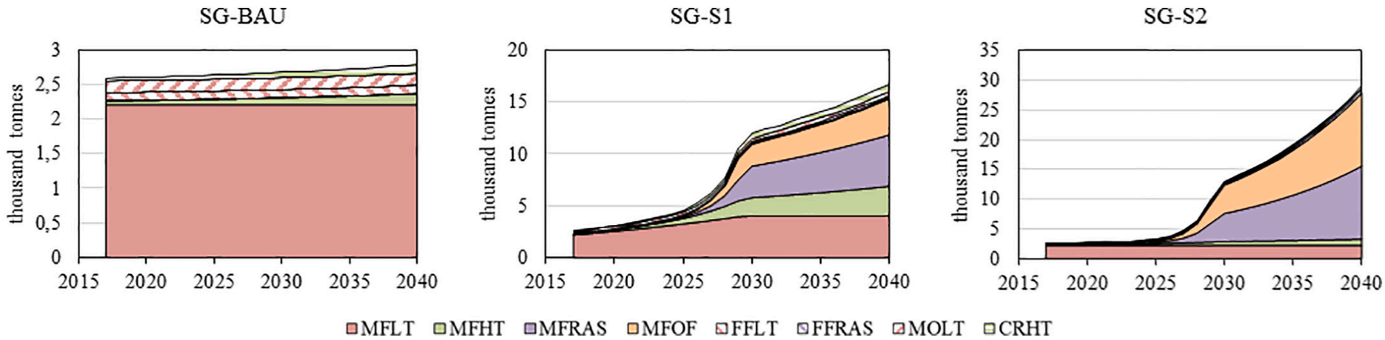

Fig. 2. Evolution in aquaculture production for the 8 production categories under the 3 scenarios for Singapore during, 2017–2040 (SG = Singapore; BAU = business-as-usual; S1 = scenario 1; S2 = scenario 2; MF = marine fishes; FF = freshwater fishes; MO = mollusks; CR = crustaceans; LT = low-tech; HT = high-tech; RAS = recirculating aquaculture system; OF = offshore). Note the different scale on y-axis between the graphs.

Table 2
Description of the current and future aquaculture systems in Norway with abbreviations, differentiation between juveniles and grow-out when needed, feed type, and whether it is a closed or open system. Future technologies are indicated with a "*" symbol.

Species group	Technology type	Category abbreviation	Juveniles growth	Grow-out system	Feed	Open /closed
Salmonids	Sea cages	SASC	Fiberglass tanks equipped with highly optimized water recirculating system (RAS).	Large cages in the sea built close from the shore, often in fjords.	Dry pellets	Open
	RAS*	SARAS*	Fiberglass tanks equipped with highly optimized water recirculating system.		Dry pellets	Closed
	Offshore*	SAOF*	Fiberglass tanks equipped with optimized water recirculating system (RAS).	Large cages in the sea built far from the shore.	Dry pellets	Open
	IMTA*	SAINT*	Fiberglass tanks equipped with highly optimized water recirculating system (RAS).	Large cages in the sea built close from the shore, often in fjords, with mussels long lines built strategically close to reduce nutrient emissions.	Dry pellets	Open
Mollusks	IMTA*	MOINT*	Long lines attached to wooden polls close to the shore, built strategically close to salmonids farmed in sea cages in order to feed on their nutrient emissions.		Unfed	Open
White fishes	Sea cages	WFSC	Fiberglass tanks equipped with highly optimized water recirculating system (RAS).	Large cages in the sea built close from the shore, often in fjords.	Dry pellets	Open

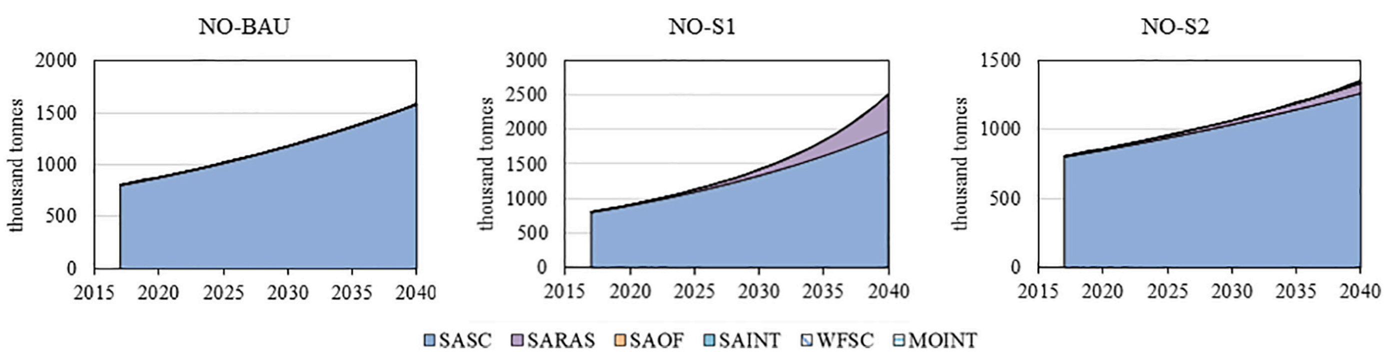

Fig. 3. Evolution in aquaculture production for the 6 production categories under the 3 scenarios for Norway during, 2017–2040 (NO=Norway; BAU = business-as-usual; S1 = scenario 1; S2 = scenario 2; SA = salmonids; WF = white fishes; MO = mollusks; SC = sea cages; RAS = recirculating aquaculture system; OF = offshore; INT = integrated multi-trophic aquaculture). Note the different scale on y-axis between the graphs and that SAOF, SAINT, WFSC and MOINT are not visible on the graphs due to their low proportions relative to SASC and SARAS.

industry in the current economic situation of the country, as explained in Supplementary Methods. The obtained production of the different aquaculture categories is illustrated for the 3 scenarios in Fig. 3.

2.3. Life cycle assessment study (Step 3)

In the following sections, the scope definitions (Section 2.3.1), life cycle inventories (Section 2.3.2) and life cycle impact assessments (Section 2.3.3) of both case studies are described.

2.3.1. Scope definition

The functional unit (FU) of this LCA is defined as the average production (over a year) of 1 ton of edible seafood in Singapore/Norway in the period, 2017–2040. In other words, the impacts from the different production categories are weighted according to the yearly production of each technology type and normalized by the total production of that year. The resulting "normalized impacts" reflect the eco-efficiency of aquaculture production in the country (but in an opposite way, as the eco-efficiency increases when the normalized impacts decrease). These are calculated for each year of the reference time period to obtain the evolution of the normalized impacts through time. A FU reflecting the average impacts of the aquaculture sector has been preferred over one accounting for the total impacts of the industry because of the large variation in terms of total annual production between the scenarios assessed for each country. Only looking at the total impacts per year would therefore induce a bias and could lead to misleading conclusions. However, the total impacts for climate change are disclosed in Supplementary Results and discussed in the discussion section in parallel with the annual production quantities.

The boundaries of the analyzed systems are described in Fig. 1 (Step 3) and contain fingerling/smolt production, infrastructures, consumables (e.g. oxygen and cleaning products), feed, farming (including water and energy consumption and nutrient emissions or avoided production of fertilizer) and post-farming. Due to lack of data and because they are deemed negligible, the following elements are excluded from the analyzed system: harvesting (boats and fuel), cages/nets cleaning, boats manufacturing and materials, generators manufacturing and materials, infrastructures and transport of consumables to the farms, transport of the final product to the retailer and to the consumer, storing and cooking. Usage of drugs, medicine and vaccines are excluded too because of the non-systematic nature of their usage and the lack of knowledge about the impacts of these substances. Modeling of multi-functional processes that deliver more than one product/by-productsis handled following the recommendations of the ISO standards (ISO, 2006b). In general, the co-products of ingredients used in this study (i.e. co-products of wheat flour, white rice, rape oil, sunflower oil, soybean meal, fishmeal and fish oil production) are common animal feed or human food (Asbridge, 1995; Chapoutot et al., 2019; Dronne, 2019; Sharma, 2014). Therefore no alternative conventional ways of production can be found, and allocation based on the gross energy content is applied. The use of fish residues (uneaten feed and feces) as natural fertilizers is modeled using system expansion with an avoided production of synthetic fertilizers. Algal oil production leads to two co-products that can be used as animal feed and light fuel; therefore, system expansion could be used with the avoided production of conventional products fulfilling these functions. By-products from food industries are used as feed in the Singaporean case and as inputs for FMFO production; as typically done in LCA dealing with waste generation, these are modeled as by-products with zero burden, while avoided production of the quality fish it replaces is considered to be avoided at the level of the fileting industries. The modeling follows a consequential modeling framework as defined in the ILCD Handbook (EC, 2010). Simapro v9.0.0.49 was used for the modeling construction and assessment (PRé Consultants, 2018).

2.3.2. Inventories building and system modeling

A detailed overview of the modeling, data sources and assumptions is available in Supplementary Methods. Below, the key modeling aspects are summarized.

For the Singapore case study, the LCI data originate from Bohnes and Laurent (2021), who collected onsite, primary data from several farms, covering 8 different production systems and 4 species groups (mollusks, crustaceans, marine and freshwater fishes). The future technologies' inventories were based on literature, with Liu et al. (2016) for the RAS and García García et al. (2016) for the offshore system, adapted to fit the Singaporean context. For simplicity, all feed pellets and marine ingredients are modeled as originating from Vietnam, all plant-based ingredients from China and all fingerlings from Malaysia, as these are the most common origins of these goods in the farms where onsite data were collected. Transportation of feed is calculated based on average distances from these countries to Singapore, and is assumed to happen via a combination of road and maritime transportation means. To transform live-weight mass at farm gate to mass of edible seafood, an edible ratio that varies between different species groups is used, namely 0.5 for marine fishes, 0.4 for freshwater fishes, 0.48 for mollusks (green mussels as reference) and 0.2 for crustaceans (FAO, 2019a; Garduño-Lugo et al., 2003; Jankowska et al., 2007; Rivonker et al., 1993; US.FOODS, 2018). Fileting and gutting are needed for marine fishes produced in"high-tech" and offshore systems as the average size of a produced fish is around 4 to 5 kg, and is based on Winther et al. (2009). Other technologies usually produce small specimens (app. 0.5–1 kg) that are sold as entire fishes in supermarkets to accommodate local cooking habits.

For the Norway case study, data were gathered from literature and governmental reports to build inventories representative of Norwegian aquaculture for the six production systems of the study. The sea cages systems and the RAS were based on Liu et al. (2016) and the offshore on García García et al. (2016), adapted to the Norwegian context. The mussel production of the IMTA was based on Lourguioui et al. (2017), the enhanced production factor, thanks to the presence of both species, relied on Reid et al. (2008), and the typical mussels/salmons ratio of such a production site built on Whitmarsh et al. (2006). All feed pellets and marine ingredients are modeled as originating from Norway, all plant-based ingredients from France except soybean from Brazil, and all fingerlingsfrom Norway, as these are the most common origins of these products (Winther et al., 2009). Transportation of feed is calculated based on average distances, and is assumed to occur via road. To transform live-weight mass at farm gate to mass of edible seafood, edible ratios that vary between different species groups are used, with values of 0.62 for salmonids, 0.36 for white fishes and 0.25 for mollusks (blue mussels as reference) (FAO, 2019a, 2019b; Bestofsea, 2019). Fileting and gutting are needed for salmonids and white fishes as the average size of a produced fish is around 3 to 5 kg, and is based on Winther et al. (2009).

In both cases, the ecoinvent v3.5 consequential database was used for modeling the background system, and some processes taken from the Agri-footprint v4.0 database were remodeled using ecoinvent processes for consistency (Durlinger et al., 2017; Wernet et al., 2016). The electricity supply for the entire aquaculture sector was modeled using national average grid mix data as they were assumed not to be impacted by large structural changes.

The prospective nature of this study implies that the inventories are generated for the reference year 2017 and then require adaptation for the period 2017–2040. Therefore, our inventories are time-differentiated throughout the whole period, reflected by yearly changes of specific parameters, including feed production, water and energy requirements during farming, FCR and electricity grid mix composition; Table 3 reports the main changes and data sources behind the variations in 2017–2040.

2.3.3. Life cycle impact assessment

The newly developed impact assessment methodology IMPACT World+ (Bulle et al., 2019) is used at both midpoint and endpoint levels to assess the environmental impacts in the two case studies. Midpoint impact categories include non-toxicity impacts (e.g. climate change, acidification, particulate matter formation), toxicity impacts (such as freshwater ecotoxicity, human toxicity), resources related impacts (e.g. water scarcity, mineral resource use, fossil and nuclear energy use, land occupation and transformation), and endpoint areas of protection (AoPs) include Ecosystems quality and Human health (resources are disregarded at AoP level due to lack of method maturity). They are all listed with their corresponding units in Supplementary Information in Table A9.

An additional midpoint impact category is assessed, the net primary production use (NPPU), which is specific to food production LCAs. Developed by Papatryphon et al. (2004), this impact category assesses the biotic resource that is occupied by the studied system and hence not available for other systems. Therefore, only feed has a contribution to this impact. NPPU of fishery-related ingredients is assessed using the formula from Pauly and Christensen (1995) which is: $NPPU = (M/9) * 10^{T-1}$, where M is the wet mass of the organism and T is its trophic level. The average trophic level of the FMFO production of this study was calculated based on the global average for the Singapore case study

Table 3
Changes in the life cycle inventories between 2017 and 2040.

Change type	Parameter/process impacted	Change within 2017–2040	
		Singapore[a]	Norway
Feed ingredients	Feed option 1 Fishmeal and fish oil production	Part of FMFO produced from by-products increases from 44% in 2017 to 80% in 2040.	Part of FM (*FO*) produced from by-products increases from 19.4% (*28,1%*) in 2017 to 70% (*80%*) in 2040.
	Feed option 2 Feed pellets production	- MFLT/FFLT/CRHT: no changes. - MFHT/MFRAS/MFOF: 50% of FO is replaced by algal oil; 37.5% of FM is replaced by insect-based meal; 12.5% of FM is replaced soybean meal. - FFRAS: 100% of the FM is replaced by insect-based meal.	- SA: 100% of FMFO replaced by insect-based meal and algal oil in 2030. - WF: 20% of FO replaced by algal oil in 2040, and FM decrease to 25% in 2040 replaced by insect-based meal.
Farming optimization	Water need	Decrease by 10 to 20% depending on technology maturity.	Decrease by 5 to 15% depending on technology maturity.
	Energy need	Decrease by 10 to 20% depending on technology maturity.	Decrease by 5 to 15% depending on technology maturity.
	Feed conversion ratio	Decrease following historical trends of the period 2000–2015.	Constant for SASC/WFSC as it is highly optimized already Decrease to 0.8 in 2030 for RAS and 1.1 in 2040 for offshore systems.
Electricity grid mix	Electricity production source and percentages	Limited change (gas remains predominant).	Hydropower remains predominant but introduction of wind power.

[a] Extracted from Bohnes and Laurent (2021).

(representative for Vietnamese production - SEAFISH, 2018) and based on an average over the three bigger Norwegian FMFO producers for the Norwegian case study (i.e. Biomar, 2018; Cargill, 2017; Skretting, 2018). The plant-based ingredients NPPU impacts are based on the crop carbon content (Papatryphon et al., 2004).

The interpretation in Step 4 has two levels of comparisons: the scenarios and the feed options. The impacts per yearly-averaged ton of edible seafood produced in either Singapore or Norway, i.e. impacts per functional unit, are hereafter called the “normalized impacts” for simplicity.

3. Exploring the future of Singaporean aquaculture

Fig. 4 presents the evolution over, 2017–2040 of the normalized impacts (i.e. per yearly-averaged ton of edible seafood produced) in Singapore. Detailed background data of Fig. 4 are available in Supplementary Table B1 and detailed results for the total impacts under each scenario are reported as well in Supplementary Table B3.

3.1. Scenario trends over 2017–2040

Normalized impacts have a rather small overall temporal variation during the period 2017–2040 in scenario SG-BAU (varies by maximum ±20% compared to 2017). Indeed, changes in the production mix are small in SG-BAU during 2017–2040, as marine fishes in “low-tech” systems add up to a minimum of 80% of the yearly production during the whole period (see Fig. 2), and are hence likely to drive the normalized impacts. This technology for marine fishes is between mature and obsolete, and the optimization potential is low, so the impacts per ton of edible marine fish produced show little variations during the timeframe. In most impact categories, normalized impacts decrease within 2017–2040. The exceptions are due to the increasing proportion of crustaceans in “high-tech” systems in the production mix, which have a much higher score in these impact categories than marine fishes in “low-tech” systems because of higher electricity use (freshwater ecotoxicity), higher infrastructures requirements (mineral resource use) and different feed composition (land transformation).

Normalized impacts in SG-S1/S2 are not lower than in SG-BAU in all impact categories, which means that choosing SG-S1/S2 over SG-BAU would lead to environmental trade-offs per unit of edible seafood produced. Such a change would create an increase in climate change, ionizing radiation, ozone layer depletion, human toxicity cancer, freshwater ecotoxicity, and fossil and nuclear energy use, while freshwater acidification, both eutrophication, photochemical oxidant formation, land occupation and transformation, and NPPU would decrease per unit of edible seafood produced. This reflects the introduction of more new technologies in the explorative scenarios’ production mix, as impacts that are generally the burdens of innovative technologies (e.g. toxicity impacts and energy-related impacts) are higher for SG-S1/SG-S2, whereas impacts mainly associated with traditional technologies (i.e. eutrophication and NPPU) are higher for SG-BAU per averaged unit of seafood produced. Normalized impacts are generally lower with Feed option 1 than with Feed option 2 in all scenarios because the production of insect-based meal has higher scores in most impact categories than fishmeal.

At endpoint level, the normalized results for ecosystem quality remain constant over 2017–2040 for SG-BAU and increase by 18–53/21–64% for SG-S1/S2, respectively, depending on the feed option. The impact category “freshwater ecotoxicity long term” is dominant in all scenarios, and the larger increase in the explorative scenarios is due to the increasing proportion of RAS production and because of their considerable consumption of consumables and electricity. In particular, Feed option 2 is associated with high scores for this impact category because the production of algal oil requires an important amount of electricity. However, high uncertainty comes with all toxicity impacts due to a large number of substances potentially contributing to environmental damages and their relatively limited coverage in current LCIA methods (UNEP SETAC, 2019). Human health normalized impacts decrease with Feed option 1 (by 12/23/26% for SG-BAU/S1/S2 respectively) and remain constant or increase slightly with Feed option 2. Damages to human health are dominated by climate change long-term and water availability, which are driven by the feed impacts (marine- as well as plant-based).

3.2. Analysis of selected impact categories

3.2.1. Climate change

Overall, climate change impacts have a limited variation, as they stay within a range of 11.3–13.7 t-CO_2eq/ton-edible-seafood produced for all years and all scenarios. In their study on Indonesia, Henriksson et al. (2017) found a climate change impact of approximately 3 to 15 t-CO_2eq per ton of live-weight seafood produced, corresponding roughly to 6–30 t-CO_2eq/ton-edible-seafood produced (with an edible fraction of marine fishes, the dominant species group, being 0.5), which is therefore consistent with the above result. Feed option 2 has higher impacts than Feed option 1 for all scenarios because insect-based feed has a higher

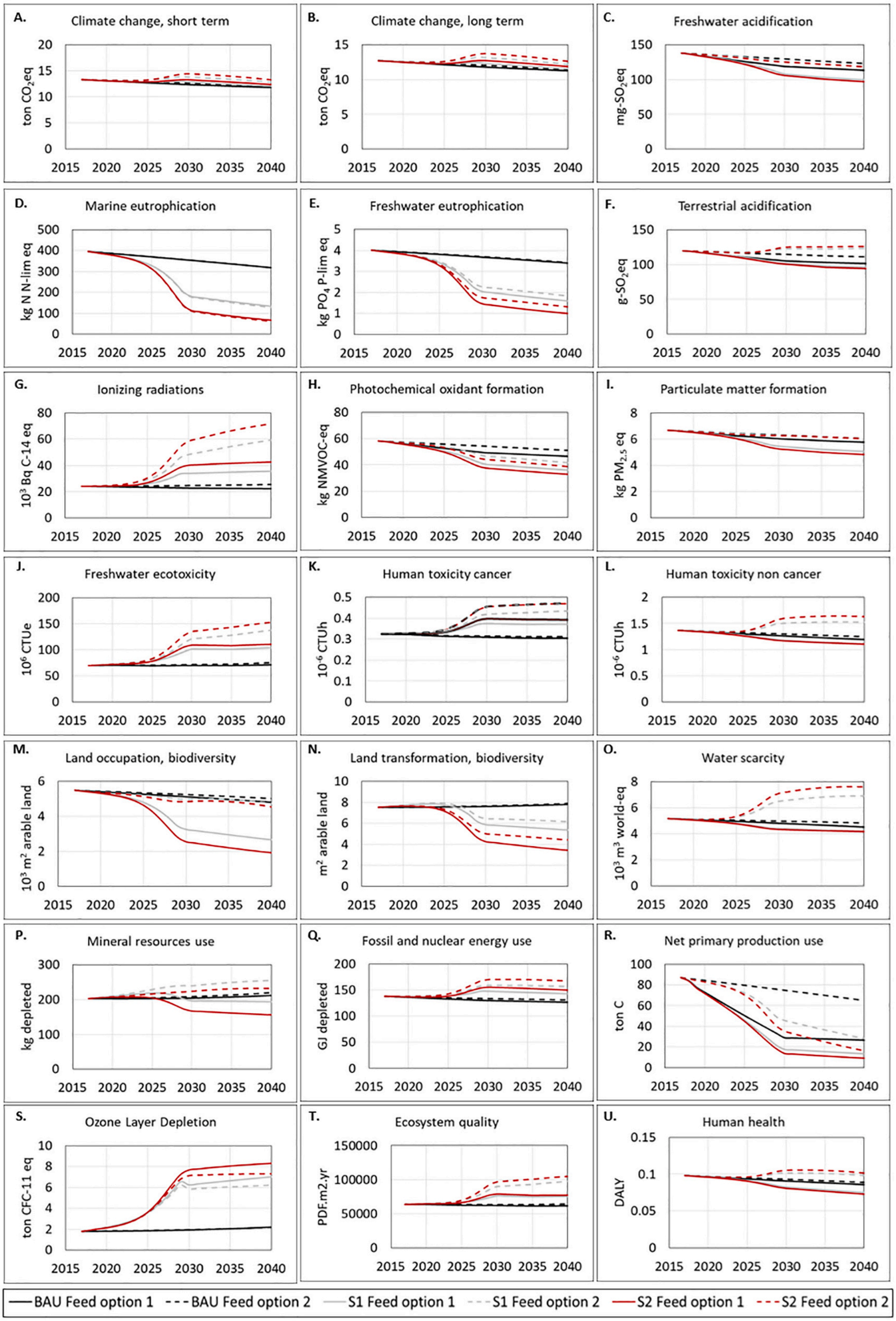

Fig. 4. Evolution between 2017 and 2040 of the impact scores for 1 yearly average ton of edible seafood produced in Singapore in the 3 scenarios with the 2 different feed options, covering 9 impact categories of IMPACT World+ midpoint and NPPU (net primary production use) (A to J) and the 2 areas of protection of IMPACT World+ endpoint (K and L). The other 9 impacts impact categories of IMPACT World+ midpoint (climate change long term, freshwater and terrestrial acidification, ionizing radiations, photochemical oxidant formation, particulate matter formation, human toxicity cancer and non-cancer, and ozone layer depletion) are available in Supplementary Information A, Fig. A7.

climate change impacts than fishmeal.

3.2.2. Eutrophication

A drastic decrease of both marine and freshwater eutrophication normalized impacts is observed in the explorative scenarios (− 60–90% depending on the Feed option and scenario). This is due to the lower proportion of marine fishes in “low-tech” systems (i.e. nets in the sea) in the production mix. “Low-tech” systems are open systems that have a high FCR, and therefore yield the highest eutrophication impacts of all production categories included in the study (Bohnes and Laurent, 2021). SG-S2’s impacts have approximately halved in 2040 compared to SG-S1, thanks to a higher proportion of RAS and other closed systems, which do not have direct nutrient emissions during grow-out.

3.2.3. Resources

NPPU is the only impact category that decreases across all scenarios and all feed options because reducing the use of marine resources is the main goal of both feed options (see Section 2). It varies within 9.2–87 tons C per ton of edible seafood produced. Bohnes et al. (2019) found an average NPPU impact of 50 tons C/ton-live-weight-seafood over 65 reviewed LCA studies, corresponding to 100 tons C/ton-edible-seafood if an edible fraction of 0.5 is considered. Therefore, NPPU impacts found in this study for Singapore are quite low compared to past studies.

Land use impacts are especially important for Singapore, due to the scarcity of this resource in the city-state. Land occupation normalized impacts decrease drastically for SG-S1 and SG-S2 with Feed option 1, and stay relatively stable with Feed option 2 with little difference across the scenarios. Indeed, the proportion of marine fishes in “low-tech” decreases with time. This category has important land occupation impacts, which for Feed option 2 is compensated by the increasing use of insect-based meal that has a higher land occupation than fishmeal. However, feed production is likely to happen outside the island, and if only land occupation in Singapore is accounted for, both Feed options engender the same decrease.

3.3. Sensitivity and uncertainty analyses

The different scenarios and options compared can be used as part of a sensitivity analysis. It appears that the results are highly sensitive to all parameters related to feed (feed composition and FCR). The changes within scenarios illustrate the influence of the technology and species on the results. In this study, the most important source of uncertainty relates to the prospective LCIs. They are intrinsically uncertain due to their construction based on assumptions and extrapolations. Similarly, the scenarios are highly uncertain as they describe future evolutions of aquaculture production. Therefore, these uncertainties could not be avoided because the main value of the study is its prospective nature.

3.4. Key messages of the Singaporean case study

Overall, the scenario SG-BAU offers decreasing normalized scores over time for most impact categories, and has less extreme variations than the two explorative scenarios (i.e. no important increase of impacts occurs but no important decrease either). Therefore, this scenario could be an acceptable solution to limit the increase of impacts per unit of edible seafood produced in general. However, Bohnes et al. (2020) concluded that the scenario SG-BAU does not allow Singapore to reach 30% of self-sufficiency by 2030 for seafood, which is the main objective of its new “30-by-30” policy. Therefore, SG-S1 and SG-S2 are more likely to become true if Singapore takes up this policy. In general, the two scenarios have the same tendency, but SG-S2 presents more extreme variations, hence SG-S2 strengthens gaps between impacts that decrease and those that increase per unit of edible seafood produced. However, except for ionizing radiation and ozone layer depletion, the difference is small (less than 7% difference in eco-efficiency over the whole period). Considering that ozone layer depletion scores are likely biased due to the use of outdated data (due to general abandonment of ozone-depleting substances since 2006), only ionizing radiation is substantially higher for SG-S2. Therefore, scenario SG-S2 may be preferred, and the Singaporean government should get inspired by the production mix obtained in this scenario to implement new incentives aimed at farmers willing to develop the different innovative technologies of SG-S2. Examples of such incentives include the implementation of financial aids for new farms willing to use these technologies and for existing ones willing to transition to them. It could also include facilitating the creation of new aquaculture companies using modern technologies, which could attract local as well as foreign investors.

The results also suggest that replacing fresh fish with trimmings in FMFO production is a more environmental-friendly option than replacing FMFO with insect-based meal and algal oil. Singapore being a modest FMFO producer, encouraging the use of FMFO from trimmings can be done through new import regulations or taxes applied on FMFO that do not comply with a minimum amount of trimmings used in their manufacturing.

4. Exploring the future of Norwegian aquaculture

Fig. 5 presents the evolution over, 2017–2040 of the normalized impacts (i.e. per yearly-averaged ton of edible seafood produced) in Norway. Detailed background data of Fig. 5 are available in Supplementary Table B2 and detailed results for the total impacts under each scenario are reported as well in Supplementary Table B4.

4.1. Scenario trends over 2017–2040

In general, the impacts per yearly-averaged ton of edible seafood show limited variations over time in NO-BAU with Feed option 1 (maximum ±15% compared to 2017). With Feed option 2, normalized impacts change more drastically during 2020–2030 in NO-BAU, and follow the flat and linear trend of Feed option 1 afterwards. This corresponds to the progressive introduction of insect-based meal and algal oil in the salmonids’ diet that occurs during this specific decade. The most drastic increase is seen with freshwater ecotoxicity, for which normalized impacts increase by more than 3-fold within 2017–2040. This is due to the combination of higher use of electricity needed for the production of the novel ingredients and the fact that the electricity mix evolves towards a higher proportion of wind energy replacing hydropower. As wind power has higher toxicity impacts than hydropower, it contributes to increasing the impacts per functional unit. The only decreasing impacts are marine and freshwater eutrophication, NPPU, land transformation and ozone layer depletion, because the novel ingredients have lower environmental impacts per kg produced in these categories than FMFO that they replace.

The two other scenarios show similar tendencies as NO-BAU, and it appears that for this case study, the feed option is much more influential than the scenario. This was expected, as the difference between scenarios is small, with the salmonids in sea cages largely dominating the whole period in the three scenarios. In general, NO-S1 and NO-S2 present lower impacts than NO-BAU, by 0–7%, except for marine and freshwater eutrophication and NPPU that are lower by around 20%. On the contrary, freshwater ecotoxicity and ionizing radiation are higher in 2040 for the two explorative scenarios compared to NO-BAU, by 3–10% for SG-S2 and 12–45% in SG-S1. The largest difference is seen for NO-S1, because the proportion of salmonids in RAS is the largest of all scenarios (21%) and this production system presents the highest impacts for these categories. In general, the difference between scenarios is lower with Feed option 2 because the impacts of feed dwarf the differences in impacts between technologies.

Similar trends are observed at endpoint, with the feed option again being more important than the type of scenarios. Normalized impacts for both Ecosystems quality and Human health increase much more over time with Feed option 2 than with Feed option 1. Ecosystem quality is

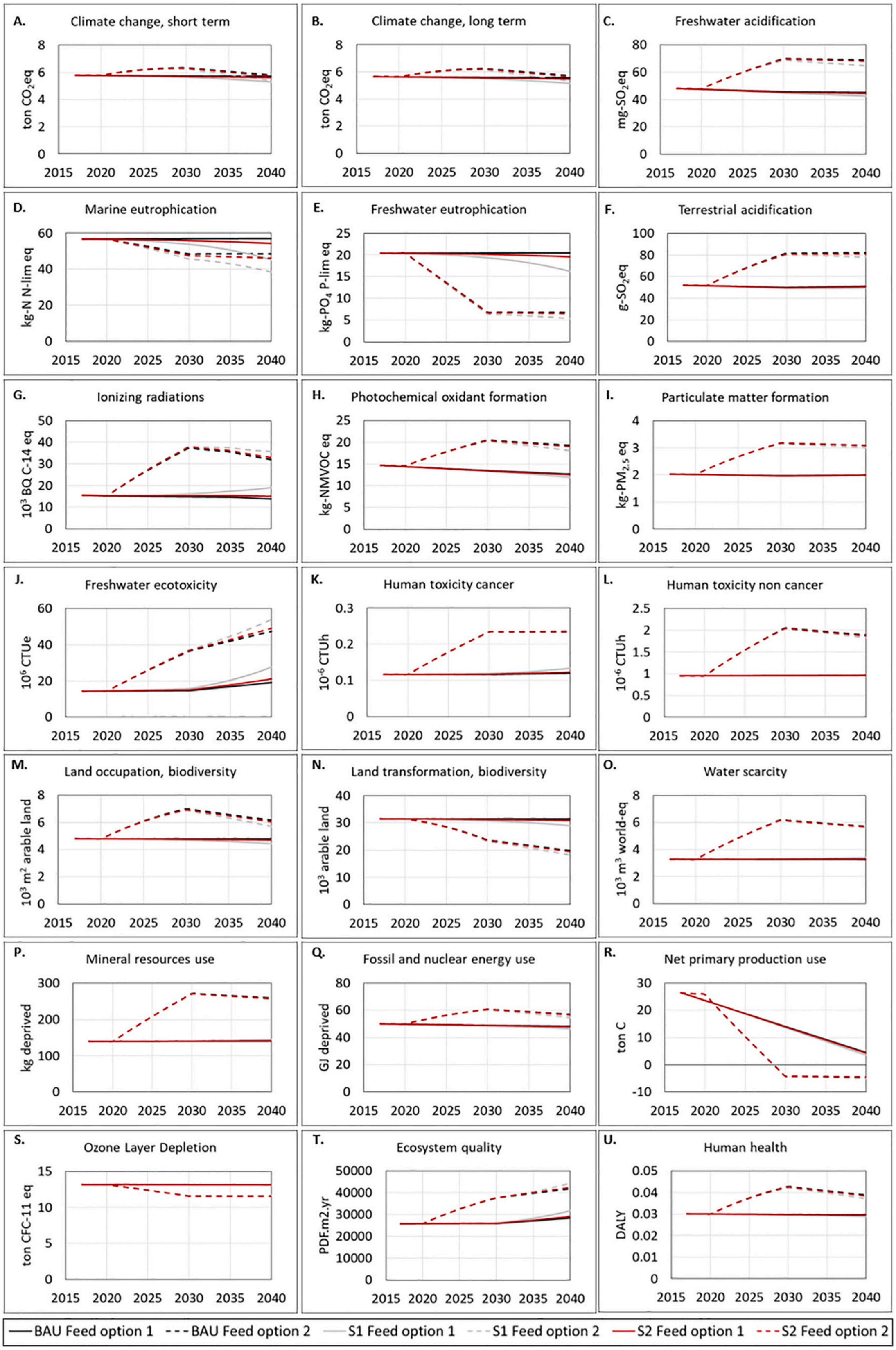

Fig. 5. Evolution between 2017 and 2040 of the impact for 1 yearly average ton of edible seafood produced in Norway in the 3 scenarios and the 2 different feed options, covering 9 impact categories of IMPACT World+ midpoint and NPPU (net primary production use) (A to J) and the 2 areas of protection of IMPACT World+ endpoint (K and L). The other 9 impacts impact categories of IMPACT World+ midpoint (climate change long term, freshwater and terrestrial acidification, ionizing radiation, photochemical oxidant formation, particulate matter formation, human toxicity cancer and non-cancer, and ozone layer depletion) are available in Supplementary Information A, Fig. A8.

dominated by freshwater ecotoxicity while Human health is dominated by climate change long-term impacts, but the difference between feed options is mainly due to water scarcity.

4.2. Analysis of selected impact categories

4.2.1. Climate change

Climate change normalized impacts show minor changes throughout the period in all scenarios. In 2040, climate change impacts are almost equal across all scenarios and all feed options. Climate change short term scores between 5 and 6 tons CO_2-eq per ton of edible seafood produced through 2017–2040, which is comparable to the 4–7 tons CO_2-eq per ton of edible salmon found by Liu et al. (2016) but a bit higher than the 2.5–4 tons CO_2-eq per ton of edible salmon from Winther et al. (2009).

4.2.2. Eutrophication

Eutrophication normalized impacts are around 20% lower in NO-S1 per ton of edible seafood produced in 2040 compared to NO-BAU in the same year. The difference is smaller for NO-S2, with only 5% lower normalized impacts than NO-BAU on average. This is due to the decrease of salmonids in sea cages in the production mix, replaced in NO-S1 by salmonids in RAS, which have no emissions of N/P in open waters during production. The feed option strongly influences the results. For example, with Feed option 2, freshwater eutrophication decreases 4-fold between 2017 and 2040 and marine eutrophication by 15%, while it stays approximately constant with Feed option 1. With this latter feed option, the composition of feed, which determines the N/P emission during production, does not change, while in Feed option 2 it is replaced by novel ingredients that present much lower N/P content, causing lower nutrient emissions due to uneaten feed and feces.

4.2.3. Resources

Regarding the resource impact categories, the difference between the scenarios is almost nonexistent making the feed option the only source of variation. Any difference in impacts is then due to a difference in the production of insect-based meal and algal oil compared to FMFO, and generally these ingredients have higher impacts. Indeed, their raw inputs (i.e. insects and algae) are cultured, whereas the raw materials of FMFO (i.e. fish) are captured, and the only impact categories that are higher for FMFO would be the ones linked to the energy use of the boats and the use of natural resources. Thus, Feed option 2 has higher impacts for land occupation, water scarcity, mineral resource use and fossil and nuclear energy use, but lower impacts for NPPU and land transformation. The decrease in land transformation is due to the co-production of animal feed, which is modeled as an avoided production of soybean meal.

4.3. Sensitivity and uncertainty analysis

The variation of the feed composition and the electricity mix through the time-scope engendered substantial changes in the impact indicator scores of the production categories. They can therefore be considered as important sources of sensitivity of the Norwegian model. Similarly to the Singaporean case study, the main source of uncertainties of this study is related to its prospective nature, and could therefore not be avoided.

4.4. Key messages of the Norwegian case study

The results of this case study suggest no clear preference for a specific scenario, as they all present similar scores over the period 2017–2040. Altogether, Feed option 1 seems to be more environmental friendly than Feed option 2 for this case study as well. Therefore, based on these findings and thanks to being a major FMFO producer, Norway could implement new regulations to impose FMFO factories to include a minimum proportion of trimmings among their raw material.

The true diversification of the Norwegian aquaculture via the implementation of new technologies or new species could not be reached in these scenarios (Supplementary Methods in Appendix A). This reflects that the economic conditions of Norway as implemented in the model do not allow such drastic transformation of the aquaculture landscape. Therefore, additional economic studies are needed to identify the factors that could be influenced to allow such change, e.g. exports/imports related parameters or expenditure behavior.

Finally, looking at the environmental impacts per ton of edible seafood produced for the different production categories, it appears that from an environmental perspective, the new technology types and species are not all interesting strategies to transition from salmonids in sea cages (see Supplementary Results in Appendix A). For instance, white fishes in sea cages have the highest environmental impacts in most impact categories, while the mollusks in IMTA have the lowest impacts of all options, in particular in marine eutrophication where it has a negative score. Negative scores here reflect an intake of nutrients from the surrounding environment, and therefore a positive effect on eutrophication (assuming over-eutrophied environment). RAS also seem to have interesting environmental characteristics compared to sea cages for salmonids, as they have lower impacts on climate change. Thus, the implementation of additional IMTA mollusks modules to existing salmonids farms or new full RAS could be encouraged by the Norwegian government through the introduction of incentives, e.g. taxes reductions.

5. Discussion

5.1. The importance of feed

The feed option was found to be very important both in Norway and in Singapore as feed dominates most impact categories for a majority of the production categories (see Table B5 in Supplementary Results and Bohnes and Laurent, 2021). Cultivation and manufacturing phases were found to contribute to the majority of the impacts, while feed transportation was found to be negligible. Increasing the proportion of trimmings in FMFO manufacturing was found to have overall the lowest environmental impacts in the two countries. However, important limitations come with the choice of this feed option.

The first is that the use of trimmings for FMFO reduction might not provide the same quality of the final product as when based on fresh fish. Indeed, using trimmings implies having little influence on the type of fish and the parts of the fish that are reduced; therefore, the feed might not contain the nutrients and fats needed for high-quality FMFO. Additionally, even though many impact categories decrease through time with the introduction of that Feed option, it has no mitigation effect on eutrophication. This impact is often considered one of the most important when it comes to aquaculture systems (Diana, 2009). The most efficient way to reduce eutrophication is to reduce the FCR, hence reducing at the origin the emissions of uneaten feed and feces. This can be done by changes in technologies or in the feed composition, like in Feed option 2. However, the ingredients assessed in Feed option 2 are not the only ones possible to replace FMFO in fishes' diets. For example, the use of microalgae is also very promising to replace fishmeal and reduce environmental impacts, as suggested by Shah et al. (2017) and confirmed in an LCA study by Seghetta et al. (2017). In our study, the algal oil introduced to replace fish oil has low environmental impacts compared to other ingredients for many impact categories, but also has drawbacks such as high electricity consumption, which in the case of both Singapore and Norway meant high human health impact at damage level. This could be overturned if the algae production improves by reducing its energy needs, or in Singapore if the electricity mix becomes more environmentally friendly. Another way to reduce eutrophication would be to improve disease prevention and hereby decreasing mortality.

Other potential candidates to replace fishmeal are leftovers from the food industry, such as chicken leftovers. These are already used in some farms in Singapore in order to reduce the costs of feed. However, some major drawbacks of this solution are (i) the low digestibility of these ingredients, which increases the FCR drastically, and (ii) their low nutrient content (Bandara, 2018). The novel understanding of the gut microbiome can help define which ingredients to prioritize in the elaboration of diets that will engender lower eutrophication impacts. Finally, plant-based ingredients have been a largely solicited solution in recent years to replace FMFO (Chakraborty et al., 2019). Nonetheless, not all vegetal ingredients are equivalent in terms of environmental impacts. For example, soybean meal is one of the most popular choices to replace fishmeal thanks to its high protein content, but its climate change impacts are among the highest of all ingredients, as found in the current study. Therefore, a diet that is nutritious for the fishes and at the same time carries the lowest environmental impacts still remains to be determined.

5.2. Climate change mitigation potential

Both countries have set climate change related targets for 2030 as a follow-up to the Paris Agreement of the COP 21 and have submitted Nationally Determined Contributions (NDCs) to the UNFCCC (UNFCCC, 2021). Singapore set two goals: (1) to reduce its emissions intensity (i.e. emissions per unit produced) by 36% below 2005 levels in 2030 and (2) to stabilize its total emissions by the same year at 65 Mt-CO_2eq (MEWR, 2018; UNFCCC, 2021). When it comes to the first goal, out of all possibilities assessed in this study, the maximum decrease of climate change normalized impacts (i.e. emissions intensity) in 2030 is obtained with SG-BAU and Feed Option 1, and is 7%. This is much lower than the target of Singapore, even when considering a potential decrease prior to 2017. However, this number is calculated applying a consumption perspective (i.e. including emissions occurring outside Singapore as a result of the consumption taking place in Singapore, e.g. Vietnamese emissions for the feed production), while the target adopts a production perspective (i.e. covering only emissions on Singapore territory). If looking only at impacts of the production stage, which could be mostly attributed to Singapore, they remain stable for SG-BAU and increase by 20% and 40% for SG-S1 and SG-S2, respectively. In this perspective, aquaculture production will not contribute to the desired reduction of emission intensity of the Singaporean government. When considering the second goal of the Singaporean government regarding climate change mitigation, the results of this study suggest that if the “30-by-30” policy is to be implemented, the aquaculture sector is likely to increase its total climate change impacts until 2040, with no stabilization in

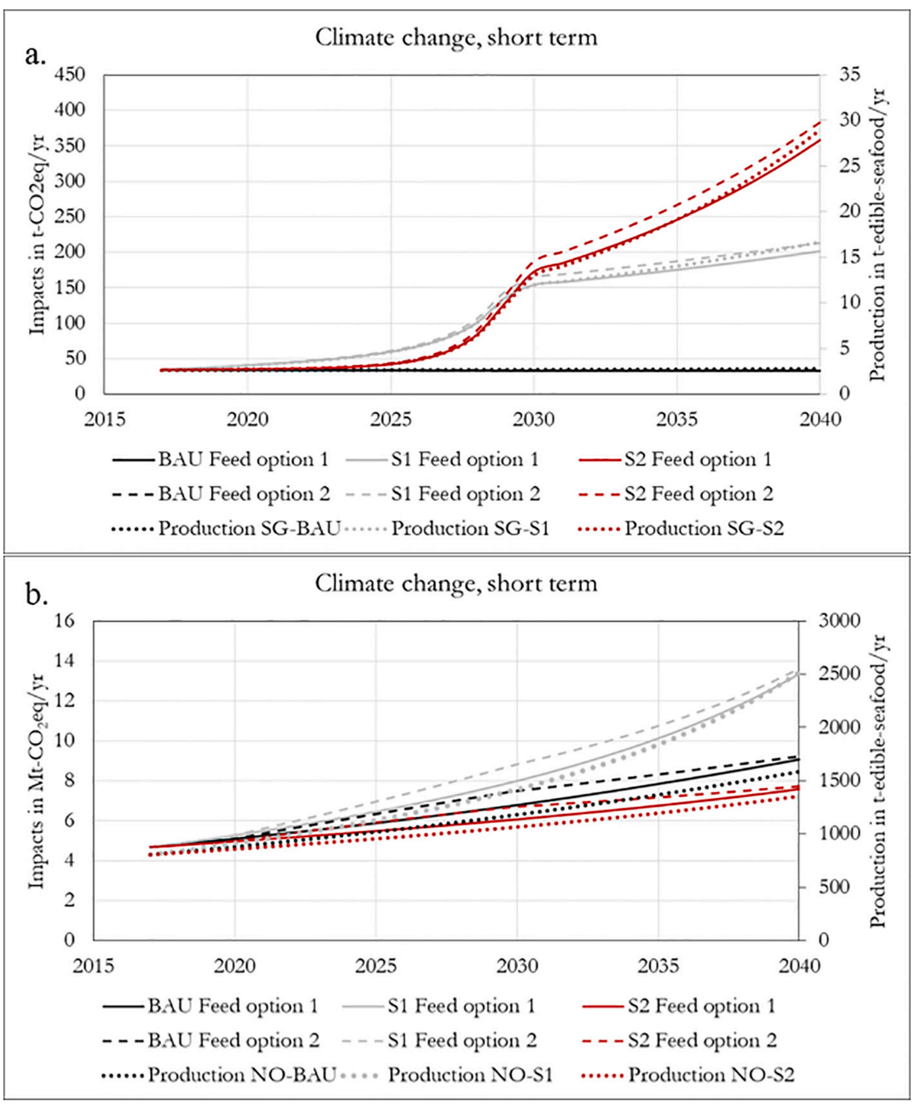

Fig. 6. Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Singapore (a) and Norway (b), with the total production of edible seafood on the secondary axis in tons per year.

2030, as illustrated in Fig. 6a. Indeed, the total production increases manifold until 2030 to fulfill the government's goal in terms of self-sufficiency, which will also contribute to increasing the total climate change impacts of that specific sector. However, Singapore's Fourth National Communication and Third Biennial Update Report emphasizes the impacts climate change can have on the country's food security, due to the low local production and high dependence on imports (National Environmental Agency, 2018). The food production sector is therefore not considered as a potential mitigation lever to decrease GHG emissions, but rather like an industry that needs development to support adaptation to climate change.

With regard to Norway, goals have been set to reduce its greenhouse gas emissions by at least 50% and towards 55% before 2030 compared to the 1990 levels (The Mission, 2019; UNFCCC, 2021). In this study, there is no decrease in the normalized impacts of aquaculture along the time period, meaning that there is no increase in eco-efficiency when it comes to climate change impacts between 2017 and 2040. With a total production that increases in all scenarios, the total climate change impacts of the aquaculture sector is anticipated to also increase (with a different increasing rate) until 2040, as illustrated in Fig. 6b. In Norway's Seventh National Communication and Third Biennial Update Report, the key role of Norway's aquaculture and fishery sectors for food security in the 130 countries Norway exports to is emphasized, together with the significant decrease in impacts that these sectors have already experienced in the last decade (Norwegian Ministry of Climate and Environment, 2018).

Therefore, it seems that neither Singapore nor Norway can rely on the aquaculture sector to reach their NDCs, or greenhouse gas (GHG) reduction goals as defined in the Paris Agreement, if they pursue the implementation of their new aquaculture policies and the resulting increases in production. However, neither Singapore nor Norway emphasized aquaculture as a strategic lever to decrease GHG emissions in their last National Communications under the UNFCCC, which suggests that the synergies between the aquaculture policies considered in this study and their climate strategies have been acknowledged in both countries (National Environmental Agency, 2018; Norwegian Ministry of Climate and Environment, 2018). They will both need to decrease more drastically the GHG emissions from other sectors to offset that increase from aquaculture.

5.3. Eco-efficiency vs. eco-effectiveness

The increase in domestic production of seafood might contribute to change Singaporean and Norwegian food habits, and increase the consumption of seafood while reducing the need for other animal proteins (Bohnes et al., 2020 and Supplementary Methods in Appendix A). Despite not being environmentally neutral, aquaculture production has been found to carry lower environmental impacts than many other livestock productions per produced food product. For example, Ogino et al. (2016) assessed different beef production systems in Thailand with LCA and obtained a climate change impact of 27 to 34 tons CO_2eq per ton of edible beef produced (considering an edible fraction of 41% - University of Tennessee Institute of Agriculture, 2019), which is at least the double of our highest results. Salmon in particular has been found to be associated with the lowest GHG emissions per energy content (Hilborn et al., 2018). Therefore, taking into account a substitution of meat with seafood, while aquaculture production might not participate in reducing national climate change eco-efficiency, it may increase the eco-effectiveness of the global food system by encouraging consumers to choose protein sources with lower environmental impacts than before and hence help meet the dietary needs of large population groups at a lower climate impact. This illustrates the relevance of the consumption-based perspective when defining climate change or other environmental targets. Indeed, the globalization of food supply chains prevents from considering countries as independent elements except in very specific cases, like those presented in this study. Norway indeed exports the vast majority of its production and Singapore imports a large majority of its consumption. Consumption-based targets allow considering the repercussions of decisions in a more comprehensive way, hence leading to higher eco-effectiveness of the global food systems, rather than only its eco-efficiency.

5.4. Lessons learned and relevance of the proposed framework for policy-making

Recommendations to decision-makers can be made on various aspects associated with aquaculture development. For example, according to the Norwegian study, the industry forecasts for the production of non-salmonids species were found to be much higher than the maximum production viable in the scenarios of this study. Therefore, a diversification of the aquaculture sector in terms of species or technologies seems to require incentives from the government. These can either occur through regulations that make the currently applied technologies more expensive than the new ones, which potentially may reduce the environmental impact, e.g. by limiting or taxing the discharges and emissions leading to important environmental impacts. The incentives can also be achieved by subsidizing cleaner technologies in the coming years.

Integrated multi-trophic aquaculture in the form of added mollusks production to existing salmonid production infrastructures appeared as a promising technique to decrease environmental impacts of existing salmonid production systems in the past literature, but was not strongly highlighted by the current study as the amount of mollusks produced was low in all our scenarios. However, looking at the impacts per edible mass produced for each species, the eutrophication reduction of the mollusks production could undeniably improve the local ecosystems quality for production in closed fjords. Based on the Singapore case study, decision-makers can get inspired regarding which species and which technologies to prioritize, as well as which consequences on the environment these choices would have. Examples are the potential environmental trade-offs that a transition from traditional technologies (i.e. platforms with nets in the sea and concrete ponds onshore) to innovative technologies (such as RAS or offshore aquaculture) would create. Additionally, the study offers the first environmental impacts baseline for Singaporean aquaculture that can be used as a benchmark for new systems and scenarios when assessing them with LCA.

5.5. Uncertainties and limitations of the proposed framework

Despite being a useful source of information for policy-makers, the proposed framework carries a number of uncertainties and limitations. In its implementation, it requires multi-disciplinary knowledge, which may be challenging to obtain. Each step of the framework thus requires specific expertise: the distribution of the aquaculture sector by species groups and technologies in Step 1 requires deep understanding in aquaculture practices and in the sectorial dynamics; Step 2 demands an advanced and practical knowledge of economics and associated modeling; and Step 3 requires mastering the application of the LCA methodology. Each step is associated with some uncertainties that are mostly case-dependent, e.g. stemming from input parameters to the models, which are dependent on data availability and data quality. The economic modeling is thus based on a simplified representation of real market mechanisms due to limited parameters and simplified assumptions (see Bohnes et al., 2020 for more details on the limitations of the economic model). Likewise, the LCA modeling embodies several uncertainties, among which the impact assessment is an important source, e.g. high uncertainty in toxicity-related impact assessment, gaps in impact categories specific to aquaculture issues (see e.g. Bohnes and Laurent, 2019 for more details on this topic). The combination of these uncertainties over all three steps of the framework is difficult to assess. Techniques to quantify them should be further investigated, while practitioners could still rely on qualitative evaluation until reliable approaches are developed. This may be facilitated if a common umbrella modeling structure is developed, in which all three steps, accompanied with their modeling, are consistently embedded. Further research to arrive at such modeling structure is still needed.

6. Conclusions and recommendations

The framework presented in this paper has been successfully applied to two countries with very different aquaculture sectors, which supports its adaptability and possible transfer to other countries. In the Singapore case study, a scenario that could allow the local government to reach its production targets has been developed, and it suggests that the development of highly innovative technologies is key. In the Norway case study, in contrast, it has been found that the objectives of the local government could not be reached in the current economic situation, and that more important incentives from the authorities are required. Both case studies suggest that the replacement of fresh fish by trimmings in the manufacturing of FMFO would reduce impacts on the environment. In both case studies, the evolution of the aquaculture sector as described by the developed scenarios also implies an increase of the total sectorial emissions of greenhouse gases between 2016 and 2040, which might appear problematic when considering that both countries have engagements for greenhouse gas emissions reduction in the Paris Agreement. However, such increases in aquaculture production may be associated with a change in consumer's habits, switching from other protein sources such as beef or lamb to seafood, which could ultimately engender a reduction of the total greenhouse gas emissions at the level of the food sector. The application of our proposed framework to the entire food sector is thus recommended when addressing such policy context beyond the sole scope of the aquaculture sector.

Although we demonstrated the operability and relevance of our proposed framework in a policy context, we acknowledge that a number of current uncertainties and limitations should be addressed to improve its reliability and accessibility to future practitioners. These research needs and associated recommendations are briefly described below for future uptake by scientists and stakeholders in the aquaculture sector:

- *Accessibility to representative data*. In the Singaporean case study, economic data with adapted species differentiation, such as trade quantities, prices or elasticities, were not available, which compelled us to adapt other data to the needs of the study based on assumptions, hence decreasing accuracy. There is therefore a research need for more economic studies on aquaculture related topics, such as elasticities of aquaculture products in various countries, and for a better accessibility to economic data in seafood production from government organizations.
- *Development of a more user-friendly economic model*. To conduct a trustworthy study, the practitioner of this framework needs to have appropriate knowledge of both LCA and economic models, when commonly they would be either LCA practitioners or economists. Therefore, we call for the development of economic models that are more user-friendly, and would not require a modeler's expertise to apply.
- *Development of impact categories specific to aquaculture issues*. Some environmental impacts are not included in common LCIA methods yet. For example, there is no method today to assess the impacts on local ecosystems of escapes of farmed fishes (Bohnes and Laurent, 2019). The development of impact categories that cover all environmental issues of aquaculture are therefore crucial for true sustainability of the sector, and research should focus on developing these missing impact pathways.
- *Integration of an absolute environmental sustainability module in supply-demand economic models*. As it is today, the framework needs two main and separate steps to be conducted. If the environmental impacts were directly implemented in the economic model, the impact assessment could be enhanced to reflect absolute sustainability in terms of the ability of the different production systems to avoid exceeding the locally determined carrying capacities of the exposed marine ecosystems. This would allow building scenarios of aquaculture development that are environmentally sustainable in absolute terms (Bjørn et al., 2016; Bjørn et al., 2015). Therefore, the integration of an absolute sustainability module in economic models such as Asiafish would allow a more comprehensive coverage of the implications of aquaculture policies' implementation, ease their interpretation and eventually produce more reliable recommendations to policy-makers.
- *Development of a framework that combines LCA and food safety risk assessment*. Only environmental impacts are assessed here. Food production systems have risks for damage to human health that are not assessed through a normal LCA. Different technologies of production are associated with different risks linked to the presence and spreading of diseases and the use of antimicrobials to treat them. It has been proven that antimicrobial use in aquaculture leads to antimicrobial resistance, which is considered by the World Health Organization as one of the most serious threats to global health currently (Santos and Ramos, 2018; WHO, 2018). In addition, the use of antimicrobials in fish feed for growth promotion (which is still rampant in most of Asia, but banned in the EU) will most likely be banned globally over the next decade, resulting in regulatory pressure on aquaculture systems for management optimization (Wu, 2019). To provide integrated, science-based decision support, food safety risk assessment could be combined with LCA and used to assess optimized solutions for selected issues such as antimicrobial resistance. Methods to ensure such combination are yet to be developed.
- *Implementation of a life cycle sustainability assessment (LCSA)*. Only the environmental dimension of sustainability is assessed in the current framework, despite the importance of the economic and social dimensions to achieve comprehensive sustainability. The implementation of a social life cycle assessment would allow the quantification of social impacts such as fair salaries, hours worked per day or health and safety in the workplace, while the implementation of an "economic life cycle assessment" could account for economic impacts such as profitability, productivity or business diversity (Kühnen and Hahn, 2018; Neugebauer et al., 2016). These impacts are particularly relevant to assess in large-scale studies like in the current study, due to the extent of the economic and social changes it can engender. Method developments are however required for developing scientifically robust and broadly-accepted frameworks for social and economic LCA that truly capture social and economic sustainability, respectively.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2021.737717.

References

Abate, T.G., Nielsen, R., Tveterås, R., 2016. Stringency of environmental regulation and aquaculture growth: a cross-country analysis. Aquac. Econ. Manag. 20, 201–221. https://doi.org/10.1080/13657305.2016.1156191.

Abate, T.G., Nielsen, R., Nielsen, M., 2018. Agency rivalry in a shared regulatory space and its impact on social welfare: the case of aquaculture regulation. Aquac. Econ. Manag. 22, 27–48. https://doi.org/10.1080/13657305.2017.1334243.

Anderson, J.L., Asche, F., Garlock, T., 2019. Economics of aquaculture policy and regulation. Annu. Rev. Resour. Econ. 11, 1–23. https://doi.org/10.1146/annurev-resource-100518-093750.

Asbridge, D.D., 1995. Soybeans vs. Other Vegetable Oils as a Source of Edible Oil Products, Practical Handbook of Soybean Processing and Utilization. AOCS Press. https://doi.org/10.1016/b978-0-935315-63-9.50005-x.

Bandara, T., 2018. Alternative feed ingredients in aquaculture : opportunities and challenges. J. Entomol. Zool. Stud. 6, 3087–3094.

Bestofsea, 2019. Blue Cultures Mussels – Atlantic Canada's Finest. Available at: http://bestofsea.com/wp-content/uploads/2015/11/Mussels_Guide_Spreads_P9.pdf.

Biomar, 2018. Sustainability Report 2018. https://doi.org/10.1056/NEJM193612032152313.

Bjørn, A., Diamond, M., Owsianiak, M., Verzat, B., Hauschild, M.Z., 2015. Strengthening the link between life cycle assessment and indicators for absolute sustainability to support development within planetary boundaries. Environ. Sci. Technol. 49, 6370–6371. https://doi.org/10.1021/acs.est.5b02106.

Bjørn, A., Margni, M., Roy, P.O., Bulle, C., Hauschild, M.Z., 2016. A proposal to measure absolute environmental sustainability in life cycle assessment. Ecol. Indic. 63, 1–13. https://doi.org/10.1016/j.ecolind.2015.11.046.

Bohnes, F.A., Laurent, A., 2019. LCA of aquaculture systems: methodological issues and potential improvements. Int. J. Life Cycle Assess. 24, 324–337. https://doi.org/10.1007/s11367-018-1517-x.

Bohnes, F.A., Laurent, A., 2021. Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore. Aquaculture 532 (736001), 1–17.

Bohnes, F.A., Hauschild, M.Z., Schlundt, J., Laurent, A., 2019. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. Rev. Aquac. 11, 1061–1079. https://doi.org/10.1111/raq.12280.

Bohnes, F.A., Rodriguez, U.P., Nielsen, M., Laurent, A., 2020. Are aquaculture growth policies in high-income countries due diligence or illusionary dreams? Foreseeing policy implications on seafood production in Singapore. Food Policy 93, 101885. https://doi.org/10.1016/j.foodpol.2020.101885.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R.K., Roy, P.O., Shaked, S., Fantke, P., Jolliet, O., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. Int. J. Life Cycle Assess. 1653–1674 https://doi.org/10.1007/s11367-019-01583-0.

Cargill, 2017. Cargill Aqua Nutrition Sustainability Report 2017 Contents.

Chakraborty, P., Mallik, A., Sarang, N., Lingam, S.S., 2019. A review on alternative plant protein sources available for future sustainable aqua feed production. Int. J. Chem. Stud. 7.

Chapoutot, P., Rouillé, B., Sauvant, D., Renaud, B., 2019. Les coproduits de l'industrie agro-alimentaire : des ressources alimentaires de qualité à ne pas négliger. INRA Prod. Anim. 31, 201–220. https://doi.org/10.20870/productions-animales.2018.31.3.2353.

Costa-Pierce, B.A., 2010. Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. Mar. Technol. Soc. J. 44, 88–112. https://doi.org/10.4031/MTSJ.44.3.3.

Dalsgaard, J., Lund, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K., Pedersen, P.B., 2013. Farming different species in RAS in Nordic countries: current status and future perspectives. Aquac. Eng. 53, 2–13. https://doi.org/10.1016/j.aquaeng.2012.11.008.

Dey, M.M., Briones, R.M., Ahmed, M., 2005. Disaggregated analysis of fish supply, demand, and trade in Asia: baseline model and estimation strategy. Aquac. Econ. Manag. 9, 113–139. https://doi.org/10.1080/13657300590961555.

Diana, J.S., 2009. Aquaculture production and biodiversity conservation. Bioscience 59, 27–38. https://doi.org/10.1525/bio.2009.59.1.7.

Dronne, Y., 2019. Les matières premières agricoles pour l'alimentation humaine et animale : l'UE et la France. INRA Prod. Anim. 31, 181–200. https://doi.org/10.20870/productions-animales.2018.31.3.2347.

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-Footprint 4.0 - Part 1: Methodology and Basic Principles. Gouda (NL).

EAT-Lancet Commission, 2019. Healthy Diets from Sustainable Food Systems -Food Planet Health.

EC, 2010. International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment - Detailed Guidance, First ed. Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/38479.

FAO, 2011. Report of the Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption. January 2010, FAO Fisheries and Aquaculture Report No. 978.

FAO, 2016. The State of World Fisheries and Aquaculture. Food and Agriculture Organisation of the United Nations, Rome, IT.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Rome, Italy.

FAO, 2019a. Yield and composition of surveyed species, in order of English name. Available at. http://www.fao.org/3/T0219E/T0219E01.htm (Accessed on December 6, 2019a).

FAO, 2019b. Cod Fish. Available at. http://www.fao.org/3/x5911e/x5911e01.htm#Physical%20composition%20and%20yields (Accessed on December 6, 2019b).

FAOSTAT, 2019. Global Aquaculture Production 1950–2017. Available at: http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en.

García García, B., Rosique Jiménez, C., Aguado-Giménez, F., García García, J., 2016. Life cycle assessment of gilthead Seabream (Sparus aurata) production in offshore fish farms. Sustainability 8, 1228. https://doi.org/10.3390/su8121228.

Garduño-Lugo, M., Granados-Alvarez, I., Olvera-Novoa, M.A., Muñoz-Córdova, G., 2003. Comparison of growth, fillet yield and proximate composition between Stirling Nile tilapia (wild type) (Oreochromis niloticus, Linnaeus) and red hybrid tilapia (Florida red tilapia x Stirling red O. niloticus) males. Aquac. Res. 34, 1023–1028. https://doi.org/10.1046/j.1365-2109.2003.00904.x.

Garlock, T., Asche, F., Anderson, J., Bjørndal, T., Kumar, G., Lorenzen, K., Ropicki, A., Smith, M., Tveterås, R., 2020. A global blue revolution: aquaculture growth across regions, species, and countries. Rev. Fish. Sci. Aquac. 28, 107–116. https://doi.org/10.1080/23308249.2019.1678111.

Gausen, D., Moen, V., 1991. Large-scale escapes of farmed Atlantic salmon (*Salmo salar*) into Norwegian rivers threaten natural populations. Can. J. Fish. Aquat. Sci. 48.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., Noble, I., 2013. Sustainable development goals for people and planet. Nature 495.

Hall, S., Delaporte, A., Phillips, M.J., Beveridge, M., O'Keefe, M., 2011. BLUE FRONTIERS Managing the Environmental Costs of Aquaculture. Penang, Malaysia.

Henriksson, P.J.G., Tran, N., Mohan, C.V., Yee, C., Rodriguez, U., Suri, S., Dominguez, L., Bambang, N., Utomo, P., Hall, S., Phillips, M.J., 2017. Indonesian aquaculture futures - evaluating environmental and socioeconomic potentials and limitations. J. Clean. Prod. 162, 1482–1490. https://doi.org/10.1016/j.jclepro.2017.06.133.

Hersoug, B., 2021. Why and how to regulate Norwegian salmon production? – the history of maximum allowable biomass (MAB). Aquaculture 545. https://doi.org/10.1016/j.aquaculture.2021.737144.

Hersoug, B., Olsen, M.S., Gauteplass, A.Å., Osmundsen, T.C., Asche, F., 2021. Serving the industry or undermining the regulatory system? The use of special purpose licenses in Norwegian salmon aquaculture. Aquaculture 543. https://doi.org/10.1016/j.aquaculture.2021.736918.

Hilborn, R., Banobi, J., Hall, S.J., Pucylowski, T., Walsworth, T.E., 2018. The environmental cost of animal source foods. Front. Ecol. Environ. 16, 329–335. https://doi.org/10.1002/fee.1822.

Hognes, E.S., 2014. Marine Fish PEFCR: Screening and Recommendations. Available at. https://sjomatnorge.no/wp-content/uploads/2019/04/Marine-Fish-PEFCR-Screening-and-recommendations-report-22-11-2016-end.pdf.

Iribarren, D., Moreira, M.T., Feijoo, G., 2010. Revisiting the life cycle assessment of mussels from a sectorial perspective. J. Clean. Prod. 18, 101–111. https://doi.org/10.1016/j.jclepro.2009.10.009.

ISO, 2006a. ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. Geneva, Switzerland. https://doi.org/10.1136/bmj.332.7550.1107.

ISO, 2006b. ISO 14044:2006 - Environmental Management – Life Cycle Assessment – Requirements and Guidelines. Geneva, Switzerland.

Jankowska, B., Zakęś, Z., Zmijewski, T., Ulikowski, D., Kowalska, A., 2007. Slaughter value and flesh characteristics of European catfish (Silurus glanis) fed natural and formulated feed under different rearing conditions. Eur. Food Res. Technol. 224, 453–459. https://doi.org/10.1007/s00217-006-0349-2.

Jayanthi, M., Thirumurthy, S., Muralidhar, M., Ravichandran, P., 2018. Impact of shrimp aquaculture development on important ecosystems in India. Glob. Environ. Chang. 52, 10–21. https://doi.org/10.1016/j.gloenvcha.2018.05.005.

Larsen, R., Eilertsen, K.E., Elvevoll, E.O., 2011. Health benefits of marine foods and ingredients. Biotechnol. Adv. 29, 508–518. https://doi.org/10.1016/j.biotechadv.2011.05.017.

Lekang, O.I., 2007. Aquaculture engineering. Aquaculture Engineering. https://doi.org/10.1002/9780470995945.

Lekang, O.I., Salas-Bringas, C., Bostock, J.C., 2016. Challenges and emerging technical solutions in on-growing salmon farming. Aquac. Int. 24, 757–766. https://doi.org/10.1007/s10499-016-9994-z.

Liu, Y., Rosten, T.W., Henriksen, K., Hognes, E.S., Summerfelt, S., Vinci, B., 2016. Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): land-based closed containment system in freshwater and open net pen in seawater. Aquac. Eng. 71, 1–12. https://doi.org/10.1016/j.aquaeng.2016.01.001.

Lourguioui, H., Brigolin, D., Boulahdid, M., Pastres, R., 2017. A perspective for reducing environmental impacts of mussel culture in Algeria. Int. J. Life Cycle Assess. 1–12 https://doi.org/10.1007/s11367-017-1261-7.

MEWR, 2018. Singapore's Climate Action Plan: Take Action Today, for a Sustainable Future.

National Environment Agency, 2018. Singapore's Fourth National Communication and Third Biennial Update Report Under The United Nations Framework Convention On Climate Change. Available at: https://unfccc.int/sites/default/files/resource/067382541_Singapore-NC4-BUR3-1-Singapore%20Fourth%20National%20Communication%20and%20Third%20Biennia.pdf.
Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024. https://doi.org/10.1038/35016500.
Neugebauer, S., Forin, S., Finkbeiner, M., 2016. From life cycle costing to economic life cycle assessment - Introducing an wconomic impact pathway. Sustainability 8, 428. https://doi.org/10.3390/su8050428.
Norwegian Ministry of Climate and Environment, 2018. Norway's Seventh National Communication Under the Framework Convention on Climate Change. Available at: https://unfccc.int/files/national_reports/annex_i_natcom/submitted_natcom/application/pdf/529371_norway-nc7-br3-1-nc7_-_br3_-_final.pdf (Accessed on October 3, 2021).
Norwegian Ministry of Fisheries and Coastal Affairs, 2009. Strategy for an Environmentally Sustainable Norwegian Aquaculture Industry.
Norwegian Minitries, 2019. Blue Opportunities - The Norwegian Government's Updated Ocean Strategy.
Ogino, A., Sommart, K., Subepang, S., Mitsumori, M., Hayashi, K., Yamashita, T., Tanaka, Y., 2016. Environmental impacts of extensive and intensive beef production systems in Thailand evaluated by life cycle assessment. J. Clean. Prod. 112, 22–31. https://doi.org/10.1016/j.jclepro.2015.08.110.
Ottinger, M., Clauss, K., Kuenzer, Claudia, 2016. Aquaculture: relevance, distribution, impacts and spatial assessments - a review. Ocean Coast. Manag. 119, 244–266. https://doi.org/10.1016/j.ocecoaman.2015.10.015.
Papatryphon, E., Petit, J., Kaushik, S.J., Van Der Werf, H.M.G., 2004. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). Ambio 33, 316–323.
Pauly, D., Christensen, V., 1995. Primary production required to sustain global fisheries. Nature 374, 255–257.
PRé Consultants, 2018. Simapro 9.0.
Reid, G., Robinson, S., Chopin, T., Mullen, J., Lander, T., Sawhney, M., MacDonald, B., Haya, K., Burridge, L., Page, F., 2008. Recent developments and challenges for open-water, Integrated Multi-Trophic Aquaculture (IMTA) in the Bay of Fundy, Canada. Bull. Aquac. Assoc. Can 12.
Rivonker, C.U., Ansari, Z.A., Parulekar, A.H., 1993. Cultivation of green mussel, Perna viridis L., on a floating raft in an estuary along the west coast of India. Aquaculture 112, 47–56. https://doi.org/10.1016/0044-8486(93)90157-T.
Rosenlund, G., Halldórsson, Ó., 2007. Cod juvenile production: research and commercial developments. Aquaculture 268, 188–194. https://doi.org/10.1016/j.aquaculture.2007.04.040.
Santos, L., Ramos, F., 2018. Antimicrobial resistance in aquaculture: current knowledge and alternatives to tackle the problem. Int. J. Antimicrob. Agents 52, 135–143. https://doi.org/10.1016/j.ijantimicag.2018.03.010.
SEAFISH, 2018. Fishmeal and Fish Oil Facts and Figures. https://doi.org/10.1055/s-0030-1250663.
Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., Thomsen, M., 2017. Seaweed as innovative feedstock for energy and feed – evaluating the impacts through a life cycle assessment. J. Clean. Prod. 150, 1–15. https://doi.org/10.1016/j.jclepro.2017.02.022.
SFA, 2019. The Food We Eat. Available at: https://www.sfa.gov.sg/food-farming/singapore-food-supply/the-food-we-eat (Accessed on October 30, 2019).
Shah, M.R., Lutzu, G.A., Alam, A., Sarker, P., Kabir Chowdhury, M.A., Parsaeimehr, A., Liang, Y., Daroch, M., 2017. Microalgae in aquafeeds for a sustainable aquaculture industry. J. Appl. Phycol. https://doi.org/10.1007/s10811-017-1234-z.
Sharma, S., 2014. The Need for Feed : China's Demand for Industrialized Meat and its Impacts.
Skretting, 2018. Sustainability Report.
The Mission, 2019. Norway and the EU – Climate Change and the Environment. Available at: https://www.norway.no/en/missions/eu/values-priorities/climate-env/ (Accessed on December 13, 2019).
The Research Council of Norway, 2005. Aquaculture 2020 Transcending the Barriers – As Long As….
Tran, N., Rodriguez, U.P., Chan, C.Y., Phillips, M.J., Mohan, C.V., Henriksson, P.J.G., Koeshendrajana, S., Suri, S., Hall, S., 2017. Indonesian aquaculture futures: an analysis of fish supply and demand in Indonesia to 2030 and role of aquaculture using the AsiaFish model. Mar. Policy 79, 25–32. https://doi.org/10.1016/j.marpol.2017.02.002.
UNEP SETAC, 2019. Global Guidance on Environmental Life Cycle Impact Assessment Indicators, vol. 2.
UNFCCC, 2021. All NDCs. Available at: https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx#collapseNORFirst (Accessed on September 19, 2021).
University of Tennessee Institute of Agriculture, 2019. How Much Meat to Expect from a Beef Carcass.
US.FOODS, 2018. Common Product Yields.
Wang, X., Olsen, L.M., Reitan, K.I., Olsen, Y., 2012. Discharge of nutrient wastes from salmon farms: environmental effects, and potential for integrated multi-trophic aquaculture. Aquac. Environ. Interact. 2, 267–283. https://doi.org/10.3354/aei00044.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Whitmarsh, D.J., Cook, E.J., Black, K.D., 2006. Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmon-mussel production system. Mar. Policy 30, 293–298. https://doi.org/10.1016/j.marpol.2005.01.004.
WHO, 2018. Antimicrobial Resistance [WWW Document]. URL. http://www.who.int/antimicrobial-resistance/en/ (Accessed on January 3, 2018).
Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V., Ellingsen, H., 2009. Carbon Footprint and Energy Use of Norwegian Seafood Products. SINTEF Fisheries and Aquaculture.
Wu, Z., 2019. Antibiotic use and antibiotic resistance in food-producing animals in China, OECD Food, Agriculture and Fisheries Papers, n°134, Editions OCDE, Paris. https://doi.org/10.1787/4adba8c1-en.