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PROSPECTIVE ASSESSMENT OF THE AQUACULTURE SECTOR

NATIONAL POLICIES AND ENVIRONMENTAL IMPACTS

FLORENCE ALEXIA BOHNES

A thesis submitted in partial fulfillment of the
requirement for the degree of Doctor of Philosophy

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**Degree under the Joint Doctorate Agreement between the Technical University
of Denmark and Nanyang Technological University**

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STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

A handwritten signature in black ink, appearing to read 'Bohnes F.', written over a horizontal line.

30/01/2020

Florence Alexia Bohnes

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I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

Assoc. Prof. Alexis Laurent

31/01/2020

AUTHORSHIP ATTRIBUTION STATEMENT

This thesis contains material from 2 papers published in the following peer-reviewed journals and from 1 paper accepted at a conference in which I am listed as an author.

Section 3.1 (Chapter 3) is published as F. A Bohnes, M. Z Hauschild, J. Schlundt and A. Laurent. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture* 11, 1061-1079 (2019). DOI: 10.1111/raq.12280.

The contributions of the co-authors are as follows:

- I defined the scope of the review, collected the LCA studies in the literature and reviewed them.
- I conducted the statistical analysis and interpreted the results.
- A/Prof Laurent participated to the definition of the scope of the review and the interpretation of the results through technical advices.
- I wrote the first draft of the paper.
- Prof Schlundt and Prof Hauschild suggested additional relevant fields of analysis to be added to the analysis and the discussion.
- I added some relevant discussion items.
- Prof Schlundt, Prof Hauschild and A/Prof Laurent added relevant scientific contributions to the paper.
- I finalized the paper.

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- b. F. A. Bohnes and A. Laurent. Methodological choices of LCA applied to aquaculture systems: Critical review & recommendations. The 11th International Conference on Life Cycle Assessment of Food (LCA Food 2018) in conjunction with the 6th LCA AgriFood Asia and the 7th International Conference on Green and Sustainable Innovation (ICGSI) 16-20 October 2018, Bangkok, Thailand.

The contributions of the co-authors are as follows:

- I defined the scope of the review, collected the LCA studies in the literature and reviewed them.
- I interpreted the results.
- A/Prof Laurent participated to the definition of the scope of the review and the interpretation of the results through advices.

- I wrote the first draft of the paper.
- A/Prof Laurent added relevant scientific contributions.
- I finalized the paper.

Section 4.4 (Chapter 4) is published as Bohnes FA, Rodriguez UP, 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 101885. doi: 10.1016/j.foodpol.2020.101885

The contributions of the co-authors are as follows:

- I defined the scope of the study and collected the data.
- Prof. Nielsen was consulted regarding the data collection as an expert in the field and contributed to build the final set of data to input in the model, based on his knowledge regarding aquaculture economics in general.
- Prof. Rodriguez provided the ASIAFISH model that he developed for another country and I adapted it to Singapore, with his technical advices.
- I analyzed the results and produced the interpretation and discussion.
- A/Prof Laurent participated to the definition of the scope of the review and the interpretation of the results through technical advices.
- I wrote the first draft of the paper.
- Prof Nielsen and Prof Rodriguez suggested modifications of the first draft in terms of structure and content.
- I wrote a new version of the paper based on the suggestions of the other authors.
- Prof Rodriguez, Prof Nielsen and A/Prof Laurent added relevant scientific contributions to the paper.
- I finalized the paper.

30/01/2020

Florence Alexia Bohnes

“Food is so important because it connects our health to the health of our planet.”

Dr. Gunhild Stordalen
Founder and executive chair, EAT Foundation

PREFACE

This dissertation presents the work of a PhD project entitled “*Prospective assessment of the aquaculture sector – National policies and environmental impacts*” that took place between December 2016 and January 2020 as part of the Joint Program Agreement between the Technical University of Denmark (DTU) and Nanyang Technological University (NTU) in Singapore. In DTU (home university), the PhD student was in the Group for Quantitative Sustainability Assessments within the Sustainability Division, at the Department of Technology, Management and Economics and under the supervision of Associate Professor Alexis Laurent and Professor Michael Z. Hauschild. In NTU (host university), the student was part of the Food Technology Centre (NAFTEC), at the School for Chemical and Biological Engineering and under the supervision of Professor Jørgen Schlundt. The PhD project was funded by DTU and produced 5 scientific articles and 1 conference proceeding. Three of these are published, two others are under peer review and the last one is an advanced draft. In the dissertation, they will be referred to by roman numbers as:

Article I	Bohnes F. A., Hauschild M. Z., Schlundt J. and Laurent A. (2019) Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. <i>Reviews in Aquaculture</i> 11, 1061-1079. DOI: 10.1111/raq.12280.
Article IIa	Bohnes F. A. and Laurent A. (2019) LCA of aquaculture systems: methodological issues and potential improvements. <i>International Journal of Life Cycle Assessment</i> 24, 324–337. DOI: 10.1007/s11367-018-1517-x.
Article IIb	Bohnes F. A. and Laurent A. (2018) Methodological choices of LCA applied to aquaculture systems: Critical review & recommendations. <i>The 11th International Conference on Life Cycle Assessment of Food (LCA Food 2018) in conjunction with the 6th LCA AgriFood Asia and the 7th International Conference on Green and Sustainable Innovation (ICGSI)</i> , 172-175, 16-20 October 2018, Bangkok, Thailand.
Article III	Bohnes F.A., Rodriguez U.-P., Nielsen M. and Laurent A. Are aquaculture growth policies in high-income countries due diligence or illusionary dreams? Foreseeing policy implications on seafood production in Singapore. Manuscript submitted to <i>Food Policy</i> (major revisions from 18-01-2020).

- Article IV Bohnes F. A. and Laurent A. Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore. Manuscript submitted to *Aquaculture* (01-2020).
- Article V Bohnes F. A., Hauschild M. Z., Schlundt J., Nielsen M. and Laurent A. Environmental sustainability of future aquaculture production: Analysis of Singaporean and Norwegian policies. Manuscript drafted for *Journal for Cleaner Production*.

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I am very thankful to all my co-authors, who participated in improving greatly the quality of my papers, among which my supervisors as well as Prof. U-Primo E. Rodriguez from the University of El Baño in the Philippines and Assoc. Prof. Max Nielsen from the University of Copenhagen.

I am grateful to DTU for funding this PhD thesis and to Niels Bohr Fondet, Otto Mønstedts Fond and Oticon Fonden for their financial support during my external stays in Singapore.

Due to the fact that my PhD was part of a Joint Program DTU-NTU, I have oscillated during these 3 years of PhD between QSA (DTU, Denmark), and NAFTEC (NTU, Singapore) where I spent 10 months split within two stays. I have been extremely lucky to be part of two warmly supporting groups, where I built high-value scientific relations for potential future professional collaborations, but also friendships. In QSA, I would like to thank especially Christine Molin for her role in securing the project at the beginning, and for her assistance through the 3 years of PhD. Then, I would like to say a special *Merci* to the French Office members, Raphaëlle and Alexandra, for their soutien, from blagues to coup de gueule, as well as the new French protégée Pernille, who made these 3 years way more interesting and fun. I would also like to thank all the other current and former QSA members, from the permanent staff (or grown-ups) to the ephemeral master students, who made me question everything I thought I knew while making me believe in the importance and relevance of what I am doing, and overall made life in QSA scientifically and socially intense. In NAFTEC, I would like to thank in particular Glendon for being such a great co-PhD-buddy-partner-companion in this Joint Program (I still don't know how to call that), for making our working discussions always pertinent, for organizing many great boat trips around Singapore and for dealing with the moods (sometimes good but mostly bad) of uncles and aunties that did or did not want to participate to our study. I would also like to thank Chengcheng and Jiahua for their

collaboration on LCA related topics and for always being helpful when I was in trouble due to administrative quiproquo. I would like to thank warmly Jean and Jesus for accompanying me through my discovery of Singaporean culture and habits as friends. Finally, I would like to thank all the other members of NAFTEC for welcoming me and trying to understand my strange area of study that does not involve lab work or deadly diseases.

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Or at least make it a little better. Hopefully. ☺

SUMMARY

Today, global food production is challenged by a continuously growing world population and increasing wealth. Food demand rises drastically and constantly, and meeting this demand requires developing and improving the current food production system on a global scale. This development needs to happen in a sustainable manner to ensure that meeting the needs of the current generation does not prevent the coming generations from meeting theirs. Sustainability has three pillars, namely environmental, economic and social, but environmental sustainability is particularly important as it is a prerequisite for social and economic sustainability because society and the economy rely heavily on the well-functioning of the Earth system to thrive.

In that setting, aquaculture appears like a promising solution to tackle the global nutrition challenge, as it has been associated with more environmental-friendly production than other animal protein sources and with significant growth potential. However, despite the flourishing of audacious aquaculture growth policies in recent decades, only a few countries seem to have truly benefited from a noteworthy aquaculture development (e.g. China, Norway and Brazil). The failure of these aquaculture growth policies in other countries has been associated with a lack of prospective assessments regarding environmental, social and economic sustainability, which led to insufficient anticipation of the policies implications. There is therefore a need to develop assessment tools that would quantify the sustainability of aquaculture growth policies to foresee their implications and thereby help policy-makers to refine and adapt these policies and ultimately prevent them from failure. The environmental dimension of sustainability being essential, it should be prioritized. This leads to the following research goal: “How to assess the current and prospective environmental sustainability of aquaculture growth policies?”

By answering that research goal, this PhD project contributes to filling the gap in aquaculture policy support. It produces a framework to assess the current and prospective environmental sustainability of aquaculture growth policies. The background and context of this PhD work, as described above, are presented in chapter 1 of this manuscript, leading to the introduction of the research goal and research questions in chapter 2.

Life cycle assessment (LCA), an ISO-standardized methodology, is recognized by regulatory bodies such as the European Commission as an adapted tool to assess the environmental sustainability of products and systems and has already been extensively used to assess aquaculture systems. LCA was therefore selected as a relevant tool to include in the framework developed in this PhD work. Thus, in chapter 3, a critical literature review is conducted on LCA studies assessing aquaculture systems until mid-2017. The analysis of 65 papers gives an insight on the main findings and remaining gaps

of these studies. A discrepancy between the geographical scope of the studies retrieved and the global repartition of the aquaculture production was found, especially for the Asian continent that gathers more than 90% of the aquaculture production worldwide, to be contrasted with a representation of only 25% in the pool of LCA studies. Feed is generally found to be the most contributing life cycle stage, and several strategies have been considered to decrease its impacts such as changing diets' composition or reducing the feed conversion ratio. The technology type and the intensity level are found to be important factors influencing the environmental impacts as well, with modern and intensive technologies being usually associated with large global impacts (e.g. climate change and energy use) while traditional and extensive technologies are usually accompanied with higher local or regional impacts (e.g. eutrophication and water use). The methodological choices of the retrieved studies are also analyzed, and improvement potentials in the application of the LCA methodology are highlighted. Overall, the relevance of LCA as a decision-making tool is confirmed, and the importance of conducting large-scale studies (at country or regional level) and prospective analysis is justified.

Chapter 4 introduces the framework developed to analyze the environmental impacts of aquaculture growth policies, and describes its four steps to allow future practitioners to apply it. Step 1 consists of an in-depth description of the seafood production in the considered country, with the identification of species groups and technology types currently in use and their categorization based similar environmental profiles. An optional step O can then be applied to perform a micro-level LCA of the production categories built in step 1. In step 2, scenarios of aquaculture development are constructed using an economic demand-supply equilibrium model to reflect different ways of implementing the assessed policy. Step 3 is a macro-level LCA to quantify the environmental impact of the scenarios developed in step 2. Finally, step 4 is the interpretation phase.

In chapter 5, the developed framework is applied to two case studies: (i) the implementation of the “30-by-30” policy in Singapore and (ii) the diversification of the aquaculture sector in terms of species and technologies in Norway, both up to 2040. The Singapore case study reveals that strong political action is needed to reach the target of 30% of self-sufficiency by 2030. Two of the developed scenarios allow reaching it and one of them allowed a significant decrease in imports. The Singaporean government should therefore introduce incentives for the development of innovative technologies, in particular of recirculating aquaculture systems and marine fishes farmed in sea cages close and far from the shore, as these production categories are found to be associated with low environmental impacts and low land requirements during the farming stage. The Norwegian case study reveals that if Norway wants to remain a key actor on the global aquaculture stage with its current economic conditions, true diversification of its aquaculture sector is not possible. As a consequence, other economic studies should be

conducted to identify which economic parameter(s) should be influenced to allow such drastic changes in the aquaculture landscape. In both case studies, increasing the proportion of trimmings in the manufacturing of fishmeal and fish oil is found to have important benefits as it reduces most of the environmental impacts, while replacing fishmeal and fish oil in fishes' diets by insect-based meal and algal oil is found to increase them.

Chapter 6 discusses the operability of the framework, which was evidenced through the two very different case studies, and presents a number of improvement potentials regarding its feasibility and structure. The relevance of the framework for policy-makers is also defended therein. Finally, the main methodological limitations of the framework are reported and analyzed together with suggestions to overcome them in future works. It is concluded that to allow the framework to assess comprehensively the sustainability of aquaculture growth policies, the framework should evolve to an absolute sustainability assessment with environmental, economic, social and risk assessment modules, combined with system dynamics and accounting for all food sectors globally to truly consider all the consequence induced by the changes.

Chapter 7 summarizes the project outcomes and lists doctoral achievements in regard to the research questions. The manuscript ends with a synthetic table recapping all the recommendations emphasized throughout this PhD work to different target audiences, including aquaculture policy-makers and stakeholders, but also LCA practitioners and developers, food and resource economists, biologists and future practitioners of the developed framework.

DANSK SAMMENFATNING

I dag udfordres den globale fødevarerproduktion af en kontinuerligt voksende verdenspopulation og stigende velstand. Behovet for fødevarer stiger dramatisk og konstant, og for at imødekomme denne efterspørgsel kræves det at det nuværende fødevarerproduktionssystem udvikles og forbedres på verdensplan. Denne udvikling skal ske på en bæredygtig måde for at sikre, at det at imødekomme den nuværende generations behov ikke forhindrer de kommende generationer i at møde deres. Bæredygtighed er delt i tre søjler, miljømæssig, økonomisk og social. Miljømæssig bæredygtighed er især vigtig, idet det er en forudsætning for social og økonomisk bæredygtighed, i og med samfundet og økonomien i høj grad er afhængig af, at jordsystemet fungerer.

I den forbindelse kan akvakultur være en lovende løsning til at tackle den globale ernæringsudfordring. Akvakultur er forbundet med mere miljøvenlig produktion end andre animalske proteinkilder og har et betydeligt vækstpotentiale. På trods af øget udbredelse af vækstpolitik indenfor akvakultur i de seneste årtier, ser det ud til, at kun få lande virkelig har oplevet en bemærkelsesværdig udvikling i akvakultur (heriblandt Kina, Norge og Brasilien). Årsagen til at mange vækspolitikker ikke har været succesfulde er en manglende vurdering af fremtidig miljømæssig, social og økonomisk bæredygtighed, hvilket førte til utilstrækkelige forventninger til politikernes implikationer. Der er derfor et behov for at udvikle vurderingsværktøjer, der kan kvantificere bæredygtigheden af vækspolitikker indenfor akvakultur for at kunne forudse implikationer og derved hjælpe beslutningstagere med at forbedre og tilpasse disse politikker og i sidste ende forhindre dem i at mislykkes. Den miljømæssige dimension af bæredygtighed er væsentlig, og bør prioriteres. Dette fører til følgende formål med projektet: "Hvordan vurderes den aktuelle og fremtidige miljømæssige bæredygtighed af vækspolitikker indenfor akvakultur?"

Ved at besvare dette forskningsspørgsmål bidrager dette ph.d.-projekt til at udfylde kløften i politisk støtte til akvakultur. Det giver en metode til vurdering af den aktuelle og fremtidige miljømæssige bæredygtighed af vækspolitikker indenfor akvakultur. I kapitel 1 af dette manuskript præsenteres baggrunden og konteksten, som beskrevet ovenfor, for dette ph.d.-arbejde, hvilket fører til introduktionen af formålet med dette projekt og forskningsspørgsmålene i kapitel 2.

Livscyklusvurdering (LCA), en ISO-standardiseret metode, anerkendes af tilsynsorganer som Europa-Kommissionen, som et tilpasset værktøj til at vurdere miljømæssig bæredygtighed af produkter og systemer og bruges udbredt til at vurdere akvakultursystemer. LCA er derfor valgt som et relevant værktøj at inkludere i den metode, der er udviklet i dette ph.d.-arbejde. I kapitel 3 gennemføres derfor en kritisk litteraturgennemgang af LCA-undersøgelser, der vurderer akvakultursystemer indtil midten af 2017. Analysen af 65 artikler giver et indblik i de vigtigste fund og resterende huller i disse undersøgelser. Der konstateres en uoverensstemmelse mellem det

geografiske omfang af de fundne undersøgelser og den globale fordeling af akvakulturproduktionen, især for det asiatiske kontinent, der har mere end 90% af akvakulturproduktionen over hele verden, men er - i kontrast - kun repræsenteret i 25% af de vurderede LCA-undersøgelser. Foder ses generelt som den mest belastende livscyklusfase, og adskillige strategier er afprøvet for at reducere belastninger herfra, såsom at ændre diætens sammensætning eller reducere foderomdannelsesforholdet. Teknologitypen og intensitetsniveauet viser sig også at være vigtige faktorer, der påvirker miljøpåvirkningerne, idet moderne og intensive teknologier normalt er forbundet med store globale påvirkninger (f.eks. klimaændringer og energiforbrug), mens traditionelle og omfattende teknologier normalt medfører større lokale eller regionale påvirkninger (f.eks. eutrofiering og forbrug af vandressourcer). De metodologiske valg i de vurderede LCA-undersøgelser analyseres også, og forbedringspotentialer i anvendelsen af LCA-metoden fremhæves. Samlet set bekræftes relevansen af LCA som et beslutningsværktøj, og betydningen af at gennemføre store studier (på nationalt eller regionalt niveau) og fremtidig analyse er berettiget.

Kapitel 4 introducerer metoden, der er udviklet til at analysere miljøpåvirkningerne af vækstpolitikker indenfor akvakultur og beskriver dens fire trin for at give fremtidige brugere mulighed for at anvende den. Step 1 består af en dybdegående beskrivelse af skaldyrproduktionen i det betragtede land med identifikation af artsgrupper og teknologityper, der i øjeblikket er i brug, og deres kategorisering baseret på lignende miljøprofiler. Et valgfrit step 0 kan derefter anvendes til at udføre en LCA på mikroniveau af de produktionskategorier, der er bygget i step 1. I step 2 konstrueres scenarier for akvakulturudvikling ved hjælp af en model med økonomisk balance mellem udbud og efterspørgsel for at afspejle forskellige måder den vurderede politik kan implementeres. Step 3 er en LCA på makroniveau der kvantificerer miljøpåvirkningen af scenarierne udviklet i step 2. Til sidst, step 4 hvor en fortolkning foretages.

I kapitel 5 anvendes den udviklede metode i to casestudier: (i) implementering af "30-før-30"-politikken i Singapore og (ii) Diversificering i akvakultursektoren med hensyn til arter og teknologier i Norge frem mod 2040. Singapore-casestudiet viser, at der er behov for stærk politisk handling for at nå målet om 30% selvforsyning i 2030. To af de udviklede scenarier gør det muligt at nå det, og et af dem tilladte et betydeligt fald i importen. Den singaporeanske regering bør derfor indføre incitamenter til udvikling af innovative teknologier, især til recirkulering af akvakultursystemer og havfisk, der opdrættes i havbure tæt på og langt fra kysten, da disse produktionskategorier viser sig at være forbundet med lave miljøpåvirkninger og lavt brug af land i landbrugsfasen. Det norske casestudie viser, at hvis Norge ønsker at forblive en nøgleaktør på den globale akvakulturscene med sine nuværende økonomiske forhold, er ægte diversificering af akvakultursektoren ikke mulig. Som en konsekvens heraf bør andre økonomiske undersøgelser udføres for at identificere hvilke økonomiske parametre, der skal påvirkes for at muliggøre en sådan drastisk ændring af akvakultur. I begge casestudier viser det sig,

at en stigning i mængden af afpudsninger til fremstillingen af fiskemel og fiskeolie kan have store fordele, da det reducerer størstedelen af miljøpåvirkningerne, mens erstatning af fiskemel og fiskeolie i fiskenes diæter med insektbaseret mel og olie fra alger, derimod øger miljøpåvirkningerne.

I kapitel 6 diskuteres anvendeligheden af metoden, der er bevist gennem de to meget forskellige casestudier, og præsenterer et antal forbedringspotentialer med hensyn til metodens brugbarhed og struktur. Desuden forsvares relevansen af metoden for beslutningstagere. Endelig rapporteres og analyseres de vigtigste metodologiske begrænsninger i metoden sammen med forslag til hvordan de kan overkommes i fremtidig arbejde. Det konkluderes, at for at rammen virkelig kan vurdere bæredygtigheden af vækstpolitikker indenfor akvakultur, bør metoden udvikles med et absolut bæredygtighedsperspektiv og inkludere både miljømæssige, økonomiske, sociale og risikovurderingsmoduler, kombineret med systemdynamik og inkludere alle fødevarersektorer globalt for i sandhed at kunne vurdere konsekvensen ved ændringerne.

Kapitel 7 opsummerer projektresultaterne og lister de videnskabelige resultater ph.d.-projektet med hensyn til forskningsspørgsmålene. Manuskriptet slutter med en tabel, der sammenfatter alle de anbefalinger, der er fremhævet i hele dette ph.d.-arbejde, til forskellige målgrupper, herunder politiske beslutningstagere indenfor akvakultur og interessenter, men også LCA-praktikere og -udviklere, fødevarer- og ressourceøkonomer, biologer og fremtidige brugere af den udviklede metode.

TABLE OF CONTENTS

PREFACE.....	IV
ACKNOWLEDGEMENTS	VI
SUMMARY	VIII
DANSK SAMMENFATNING	XI
TABLE OF CONTENTS	XIV
ABBREVIATIONS.....	XVII
LIST OF FIGURES.....	XIX
LIST OF TABLES.....	XXI
CHAPTER 1 BACKGROUND AND CONTEXT.....	1
1.1 THE GLOBAL FOOD DEMAND/SUPPLY CHALLENGE.....	1
1.2 THE POTENTIAL OF AQUACULTURE	4
1.3 THE AQUACULTURE POLICY CHALLENGE	4
1.4 HOW TO ASSESS ENVIRONMENTAL SUSTAINABILITY OF AQUACULTURE POLICIES	6
CHAPTER 2 RESEARCH OBJECTIVES.....	9
CHAPTER 3 STATUS OF LCA APPLICATION ON AQUACULTURE SYSTEMS.....	11
3.1 THE LCA FRAMEWORK.....	11
3.2 WHAT CAN WE LEARN FROM PAST STUDIES?	12
3.2.1 <i>What has been assessed so far.....</i>	12
3.2.2 <i>The importance of feed.....</i>	14
3.2.3 <i>The importance of technology and intensity.....</i>	17
3.2.4 <i>LCA potential as a decision-making tool.....</i>	18
3.3 PAST METHODOLOGICAL PRACTICES AND LIMITATIONS	19
3.3.1 <i>Defining a functional unit that reflects the assessed function.....</i>	19
3.3.2 <i>Having a comprehensive life cycle coverage.....</i>	20
3.3.3 <i>Handling multifunctionality according to the ISO standards</i>	21
3.3.4 <i>Including all relevant impact categories</i>	22
3.3.5 <i>Critical interpretation of the results</i>	23
3.4 SUMMARY OF THE IDENTIFIED RECOMMENDATIONS AND RESEARCH NEEDS ...	23
CHAPTER 4 FRAMEWORK TO ASSESS FUTURE ENVIRONMENTAL IMPACTS OF AQUACULTURE POLICIES.....	25
4.1 A FLEXIBLE EX-ANTE FRAMEWORK TO ASSESS AQUACULTURE POLICIES.....	25

4.2 DESCRIBING THE SEAFOOD PRODUCTION INDUSTRY (STEP 1)	27
4.3 MICRO-SCALE LCA OF AQUACULTURE PRODUCTION CATEGORIES (STEP O)	28
4.3.1 <i>Goal and scope definition</i>	28
4.3.2 <i>Building country-representative inventories</i>	29
4.3.3 <i>Life cycle impact assessment</i>	30
4.4 DEVELOPING SCENARIOS OF AQUACULTURE DEVELOPMENT (STEP 2)	30
4.4.1 <i>Characterizing targets based on governmental policies</i>	31
4.4.2 <i>Defining scenarios</i>	32
4.4.3 <i>Adapting a demand-supply equilibrium model</i>	32
4.4.4 <i>Generating scenarios</i>	34
4.4.5 <i>Analyzing the scenarios for policy implications</i>	35
4.5 MACRO-SCALE LCA OF NATIONAL AQUACULTURE INDUSTRIES (STEP 3)	36
4.5.1 <i>Goal and scope definition</i>	36
4.5.2 <i>Building time-differentiated, country-representative inventories</i>	38
4.5.3 <i>Life cycle impact assessment: the importance of a comprehensive coverage</i>	38
4.6 INTERPRETING THE OBTAINED RESULTS (STEP 4)	38
CHAPTER 5 CURRENT AND FUTURE ENVIRONMENTAL PERFORMANCE OF THE AQUACULTURE SECTORS IN SINGAPORE AND NORWAY	40
5.1 SINGAPORE – THE “30-BY-30” TARGET	40
5.1.1 <i>Singapore willingness to increase seafood production</i>	40
5.1.2 <i>Step 1: Description of the aquaculture sector</i>	42
5.1.3 <i>Step 0: Micro-scale LCA</i>	43
5.1.4 <i>Step 2: Scenarios construction</i>	55
5.1.5 <i>Step 3: LCA methodology application</i>	60
5.1.6 <i>Step 4: Results of the national-level assessment and interpretation</i>	62
5.1.7 <i>Recommendations</i>	66
5.2 NORWAY – THE END OF THE SALMON’S REIGN?	67
5.2.1 <i>Norway willingness to change its seafood production industry</i>	67
5.2.2 <i>Step 1: Description of the aquaculture sector</i>	68
5.2.3 <i>Step 2: Scenarios construction</i>	70
5.2.4 <i>Step 3: LCA methodology application</i>	76
5.2.5 <i>Step 4: Results of the national-level assessment and interpretation</i>	78
5.2.6 <i>Recommendations</i>	80
5.3 SIMILARITIES BETWEEN THE TWO CASE STUDIES.....	81
5.3.1 <i>Dominance of feed production</i>	81
5.3.2 <i>Climate change mitigation perspective</i>	82
5.3.3 <i>Eco-efficiency vs. Eco-effectiveness</i>	84
CHAPTER 6 OPERABILITY & RELEVANCE OF THE FRAMEWORK	86
6.1 OPERABILITY CHECK & IMPROVEMENTS FOR BETTER USABILITY	86

6.2 RELEVANCE FOR POLICY-MAKING	88
6.3 IMPROVEMENT POTENTIAL DUE TO CURRENT SCOPE LIMITATIONS	89
6.3.1 <i>Including the impacts of antimicrobial resistance</i>	89
6.3.2 <i>Including economic and social sustainability</i>	90
6.3.3 <i>Assessing absolute sustainability</i>	92
6.4 WHAT WOULD THE “PERFECT” FRAMEWORK LOOK LIKE TO ASSESS SEAFOOD POLICY IMPLICATIONS?.....	94
CHAPTER 7 CONCLUSIONS & RECOMMENDATIONS	96
7.1 PROJECT OUTCOMES & DOCTORAL ACHIEVEMENTS	96
7.2 RECOMMENDATIONS & FUTURE WORK.....	98
REFERENCES	101
GLOSSARY	113
APPENDIX 1: FARMERS’ IN-DEPTH INTERVIEW GUIDE	117
APPENDIX 2: STANDARD DATA COLLECTION TABLE.....	119
PAPER I.....	121
PAPER IIA.....	159
PAPER IIB.....	174
PAPER III.....	180
PAPER IV	222
PAPER V.....	289

ABBREVIATIONS

AESA	Absolute environmental sustainability assessment
AESI	Absolute environmental sustainability indicator
AoP	Area of protection
AMR	Antimicrobial resistance
ARRA	Antimicrobial resistance risk assessment
BAU	Business-as-usual
CR-CAP	Crustaceans from capture
CR-HT	Crustaceans from “high-tech” systems
DALY	Disability-adjusted life year
E-LCA	Environmental life cycle assessment (= “normal” LCA)
EeLCA	Economic life cycle assessment
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FCR	Feed conversion ratio
FF-LT	Freshwater fishes from “low-tech” systems
FF-RAS	Freshwater fishes from recirculating aquaculture system
FMFO	Fishmeal and fish oil
FU	Functional unit
GHG	Greenhouse gases
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IMTA	Integrated multi-trophic aquaculture
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventories
LCIA	Life cycle impact assessment
MO-CAP	Mollusks from capture
MF-HT	Marine fishes from “high-tech” systems
MF-LT	Marine fishes from “low-tech” systems
MF-OF	Marine fishes from offshore systems
MF-RAS	Marine fishes from recirculating aquaculture system
MO-INT	Mollusks from integrated multi-trophic aquaculture
MO-LT	Mollusks from “low-tech” systems
NO	Norway
NPPU	Net primary production use
OF-CAP	Oily fishes from capture
PB	Planetary boundary
PDF	Potentially disappeared fraction of species
RA	Risk assessment
RAS	Recirculating aquaculture system
RESI	Relative environmental sustainability indicator
RQ	Research question
S1/S2	Scenario 1/Scenario 2
SA-CAP	Salmonids from capture

Abbreviations

SA-INT	Salmonids from integrated multi-trophic aquaculture
SA-OF	Salmonids from offshore systems
SA-RAS	Salmonids from recirculating aquaculture system
SA-SC	Salmonids from sea cages
SDG	Sustainable development goal
SFA	Singapore Food Agency
SG	Singapore
S-LCA	Social life cycle assessment
SOTA	State-of-the-art
UN	United Nations
WF-CAP	White fishes from capture
WF-SC	White fishes from sea cages
WHO	World Health Organization

LIST OF FIGURES

Figure 1: The three dimensions of sustainability with selected examples for food production systems.....	3
Figure 2: The four phases of life cycle assessment	11
Figure 3: Life cycle stages of a product or service (i.e. system) with its inputs/outputs to the ecosphere and technosphere.	12
Figure 4: Differences in geographical distribution between life cycle assessment studies and actual production of farmed seafood worldwide in 2015.....	13
Figure 5: Impacts per ton of live-weight seafood for six selected impact categories.....	14
Figure 6: Ratio of the environmental impacts of conventional diet (Conv.) compared to those of different feed diets for seven selected impacts categories.....	16
Figure 7: Ratios of the environmental impacts of intensive aquaculture systems over those of either semi-intensive or extensive aquaculture systems.	18
Figure 8: Distributions of the 65 reviewed LCA studies (a) between the different types of functional units (FU) for aquaculture and aquafeed and (b) between the different methods for handling multifunctionality, and (c) proportion of the assessments covering some key impact categories.....	20
Figure 9: Different stages and processes of aquaculture production and types of system boundaries	21
Figure 10: General overview of the framework developed in this thesis.....	26
Figure 11: Structure of the framework for Step 2 and its five associated sub-steps (2.1 to 2.5) to assess national policies on seafood production future.....	31
Figure 12: Structure of the original Asiafish model (A) compared to the structure of the adapted Asiafish model (B).	34
Figure 13: Ranking of the 8 technologies for the 11 assessed environmental impact indicators.....	50
Figure 14: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2017 for the 8 production systems under study.....	51
Figure 15: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2040 for the 8 production systems under study.....	52
Figure 16: Structure of the AsiaFish model adapted for Singapore, with the different supply, demand and matching categories, i.e. trade.....	556
Figure 17: Total domestic production, consumption and imports of fresh fish and processed fish in Singapore for the three scenarios during the period 2017-2040.....	58
Figure 18: Domestic production (a) and annual distribution (b) for each of the species and technologies and the 3 scenarios in Singapore, and the years 2017, 2030 and 2040.	59
Figure 19: Evolution between 2017 and 2040 of the characterized scores corresponding to 1 yearly average ton of edible seafood produced in Singapore in the 3 scenarios and the 2 different feed options, for the 18 impact categories of IMPACT World+ midpoint	

and NPPU (net primary production use) (A to S) and for the 2 areas of protection of IMPACT World+ endpoint (T and U).....	63
Figure 20: Structure of the AsiaFish model adapted for Norway, with the different supply, demand and matching categories, i.e. trade.....	71
Figure 21: Total domestic production, consumption and imports of fresh fish and processed fish in Norway for the three scenarios during the period 2017-2040	73
Figure 22: Domestic seafood production (a) and annual distribution (b) for each of the species and technologies and for the 3 scenarios in Norway, and the years 2017, 2030 and 2040.	75
Figure 23: Domestic aquaculture production for each production category in the 3 scenarios, and the years 2017, 2030 and 2040 for Norway.....	75
Figure 24: Evolution between 2017 and 2040 of the characterized scores corresponding to 1 yearly average ton of edible seafood produced in Norway in the 3 scenarios and the 2 different feed options, for the 18 impact categories of IMPACT World+ midpoint and net primary production use (A to S) and for the 2 areas of protection of IMPACT World+ endpoint (T and U)	79
Figure 25: Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Singapore, with the total production of edible seafood on the secondary axis in tons per year	83
Figure 26: Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Norway, with the total production of edible seafood on the secondary axis in tons per year.	84

LIST OF TABLES

Table 1: Thesis outlook with sections and corresponding publications (available in Appendix) to address research questions (RQ) and research goal (RG).....	10
Table 2: 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.	43
Table 3: Changes in the life cycle inventories of Singapore between 2017 and 2040. ...	46
Table 4: Impact categories included in this study, with their associated unit and method.	47
Table 5: Energy, land and water inputs, emissions to water, avoided products and FCR of the 8 technologies and species for the farming stage, based on the production of 1 ton of edible seafood.....	48
Table 6: Composition of the different feed used in 2017 and 2040	49
Table 7: Seafood balance for Singapore in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories.....	56
Table 8: Seafood balance for Singapore in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories.	57
Table 9: Impact categories assessed in this study with their corresponding unit and assessment level.	61
Table 10: 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.....	68
Table 11: Seafood balance for Norway in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories.....	72
Table 12: Seafood balance for Norway in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories.	72
Table 13: Changes in the life cycle inventories of Norway between 2017 and 2040.....	77
Table 14: Summary of recommendations highlighted in this PhD project with the corresponding target audience and cross-reference in the thesis.....	99

Chapter 1 BACKGROUND AND CONTEXT

1.1 THE GLOBAL FOOD DEMAND/SUPPLY CHALLENGE

As I am writing these lines, there are exactly 7,751,179,733 human beings in the world (Worldometers, 2019). This is 3 times more than in 1950. Yet the world population is not expected to stabilize before 2100 when it would have reached ca. 10.9 billion people according to the last United Nations (UN) report (United Nations, 2019a, 2019b). Adapting to this growth requires from society to constantly rethink and adjust the way it functions and it is important to ensure that this development is sustainable. Sustainable development has been defined in 1983 by the Brundtland Commission as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (The Brundtland Commission, 1983). Among all needs, nutrition is one of the most critical ones for humankind due to its physiological nature, which implies that minimum fulfillment is vital (Maslow, 1954). The increasing world population adds a burden to the global nutrition issue, because it logically involves a general growing demand for food supply. Historically the main challenge related to nutrition was hunger, and while this has not been entirely eradicated yet, the addition of elements such as growing populations and increasing global revenues participate in constantly increasing the food demand globally. Therefore, adapting food production systems is necessary to meet the growing nutritional needs of the modern world. This has been at the heart of many national and international action plans for decades now, among which the World Food Programme of the UN (since 1961) and the Anti-Hunger Programme of the Food and Agriculture Organization (FAO - 2003). This reflects the importance of national and regional decision-makers to accompany society in its changes through policies, plans and other large-scale strategies. How to change the existing global food system to meet evolving humanity needs can seem straightforward, and *prima facie*, the solution seems to be in the answer of the (simple) following question:

→ *How to produce sufficient food to fulfill the nutritional needs of the continually growing human population?*

However, nutrition is a complex topic, which cannot be reduced to the supply of a minimum quantity of arbitrary food. To fulfill the nutrition needs of current and future generations and therefore ensure sustainability, meeting food demand should be characterized not only in terms of quantity, but also based on other criteria such as safety, quality and access. The 2030 Agenda for Sustainable Development, which involved in 2015 the adoption of the Sustainable Development Goals (SDGs) by all UN Member States (United Nations, 2015), takes all these aspects into account in its second SDG “Zero Hunger” (SDG nr.2). Defined as “rethink[ing] how we grow, share and consume

our food”, the main target of this SDG is to end hunger in all forms by 2030 by ensuring access for all people to safe, nutritious and sufficient food (United Nations, 2019c). The notion of “food security” therefore emerges, defined by the FAO as the “adequate access to food in both quality and quantity” (FAO, 2019a). In SDG nr.2, food security is assessed using the Food Insecurity Experience Scale, a survey-based index that assesses the degree of food insecurity of a respondent through the frequency he/she faced some typical food-insecure situations or conditions in the previous year, such as being hungry but not being able to eat or being unable to eat healthy and nutritious food (FAO, 2019b; Ritchie et al., 2018). The latter relates to food safety and quality, characteristics that might lead to serious sanitary issues if neglected. Safe food involves the absence of harmful bacteria, viruses, parasites or chemical substances that would generate food-borne illnesses, while nutritious food refers to food containing the adequate content of nutrients that improve health, strengthen the immune system, lower the risk of non-communicable diseases and enhance longevity according to the World Health Organization (WHO, 2019a, 2019b). The former concerns food accessibility, which is a logic necessity to food security. As any other good, food has a price and low-income populations might have difficulties to afford sufficient and/or nutritious enough food. This is closely linked to SDG nr.1, i.e. “End poverty”. The key question to be answered might therefore be reformulated as:

→ *How to produce and provide sufficient safe and nutritious food to fulfill the nutritional needs of the continually growing human population?*

As such, this question considers some social and economic aspects of sustainable food supply. However, sustainability contains three dimensions: economic, social and environmental (Elkington, 1994). As illustrated in Figure 1, the three pillars of sustainability are nested, with the economic dimension embedded into the social one, itself embedded into the environmental one. This vision developed by Griggs *et al.* (2013) reflects that the 3 dimensions of sustainability cannot be equally weighted (i.e. considered equally important), as socioeconomic systems cannot be sustained without the Earth’s life support system, albeit the contrary is possible. This indicates that trade-offs between the 3 pillars are not acceptable, especially environmental sustainability, and it is only by considering the three of them that we have a chance to build a sustainable society as targeted by the SDGs.

The food production system is no exception. Hence, in addition to the above-mentioned socioeconomic requirements, food systems need to be environmentally sustainable to stand a chance at achieving global sustainable nutrition. In 2019, the EAT-Lancet Commission produced a report entitled “Healthy diets from sustainable food systems” in which they state that the environmental sustainability of food production is among the two main targets for the development of a sustainable global diet (together with health - EAT-Lancet Commission, 2019). They found that to ensure environmental sustainability, food systems need to combine “substantial shifts toward mostly plant-based dietary

patterns, dramatic reductions in food losses and waste, and major improvements in food production practices” (EAT-Lancet Commission, 2019). These solutions aim at reducing the impacts of food supply chains on the environment, which, ironically, is especially important for food systems as they rely heavily on environmental quality themselves. They are highly vulnerable to environmental changes because this directly influences their productivity through e.g. water availability and climate (Ericksen, 2008). For instance, food systems participate in climate change (Sala et al., 2017), which itself increases the risks of extreme weather events such as drought and floods, and thus put pressures on agriculture and aquaculture.

Figure 1: The three dimensions of sustainability with selected examples for food production systems. Based on Griggs *et al.* (2013).

SDG nr.2 captures all these aspects, and the fourth target entitled “sustainable food production and resilient agricultural practices” aims at “ensuring sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality” (United Nations, 2019c). The comprehensive question that we should be asking ourselves is thus:

- *How to produce and provide sufficient safe and nutritious food to fulfill the nutritional needs of the continually growing human population, while minimizing environmental impacts and adapting to climate change?*

It is only by tackling this last question comprehensively that we will ensure true sustainability of food production and make possible to meet the current and future needs

of our society. This PhD project falls within the wide perspective of the discussion this question rises.

1.2 THE POTENTIAL OF AQUACULTURE

In that context, seafood appears as a strategic food item to produce. A seafood diet has proven health benefits thanks to its high content in healthy long-chain fatty acids, protein, vitamins and minerals (FAO, 2011). As for all other food products, the consumption of seafood presents a risk of contamination by food-borne illnesses, but risks are minimal if products are handled properly (Seafood Health Facts, 2019). Some studies claimed that seafood has lower environmental impacts than other animal protein sources (Hall et al., 2011; Hilborn et al., 2018). Finally, the potential for increasing seafood production is considerable, and at affordable cost, thanks to aquaculture (FAO, 2016).

Seafood supply originates from either wild fisheries or aquaculture. Capture fisheries were largely dominant historically, but reached a development threshold recently due to the state of wild stocks, found to be fished at maximally sustainable to unsustainable levels for around 60% of all stocks (FAO, 2018a). Oppositely, aquaculture production was very limited until the 70s, but has grown drastically since then and provides today more than half of the supply of seafood for direct human consumption (FAO, 2016). Fish farming can be a great ally to improve food security as traditional forms of aquaculture (e.g. rice-fish production or other polyculture systems) allow producing high-quality protein-based products for accessible prices (FAO, 2018a; Rajee and Mun, 2017; Troell et al., 2014). For instance, several studies have shown that the increase in aquaculture production participated in decreasing poverty in Bangladesh (Rashid et al., 2019; Toufique and Belton, 2014). All in all, it is not surprising that aquaculture is and is expected to remain the fastest growing food production sector (FAO, 2016).

Aquaculture appears as a promising solution to solve the nutrition issue raised in the previous section, and could be the “simple” answer to the complex question built previously. This is the reason why this PhD project focused on seafood production, and in particular on aquaculture. However, for aquaculture to be the solution to this great issue, not only should all implications on sustainability be thoroughly analyzed (see Figure 1), but also the reliability and viability of an important increase of aquaculture production.

1.3 THE AQUACULTURE POLICY CHALLENGE

Strengthened by all these benefits, increasing aquaculture production appears extremely attractive for fighting malnutrition in both low- and high-income countries, even though for different reasons. While in the former, it is mainly driven by the opportunity to reduce undernutrition, in the latter, the interest is in reducing overweight thanks to the health

benefits of seafood products. Indeed, one of the major nutritional issues in high-income countries is diseases associated with poor nutrition such as overweight and obesity (even though both undernutrition and overweight exist in both types of countries - WHO, 2019b). The perspective of boosting economic activity in remote areas further enhances the attractiveness of aquaculture.

Consequently, encouraging aquaculture development has been on top of many governments' agenda, and aquaculture growth policies recently flourished worldwide. Established at national or regional levels, these policies aimed at triggering a local "Blue Revolution". For instance, Bangladesh elaborated in 2012 a strategy and action plan whose goal was to increase its fish farming supply, productivity and profitability by 50% before 2020 (FAO, 2014). Another example is the European Union (EU), where the European Commission encouraged its Member States to produce multiannual national plans describing its aquaculture development strategy, with a focus on sustainability (COM, 2013). However, despite all these development plans and governmental strategies, a Blue Revolution actually happened only in a few places. Leaving aside noteworthy exceptions such as Norway, Bangladesh or Chile, aquaculture production has been truly remarkable only in China, where 65% of the world production originates (Costa-Pierce, 2010; FAO, 2016). Most aquaculture policies implemented in recent years seem to have failed at reaching their growth objectives. In the EU, aquaculture production decreased by 8% between 2000 and 2016 despite high subsidies during these years (Guillen et al., 2019). Similarly, the Canadian shellfish farming sector received important subsidies during 10 years with the objective of multiplying its production by 10-fold, but it only doubled within that period (Howlett and Rayner, 2004).

Why did these policies fail? Some authors highlighted the little consideration of relevant stakeholders during these policies elaboration, termed the "people-policy gap", which would have made the policies more realistic and accepted (Ertör and Ortega-Cerdà, 2017; Krause et al., 2015). Others denounced an inadequate knowledge of the environmental implications of such policies and the lack of science-based assessment beforehand, or the "science-policy gap" (Dürrenberger et al., 1999). Finally, Anderson et al. (2019) evoked the limited consultation of economists on the design and evaluation of these policies that would have contributed to limiting the growth of local aquaculture industries. Overall, a general lack of prospective evaluation of future implications of aquaculture policies regarding the three sustainability dimensions appears as the main cause of their failure.

How to design aquaculture growth policies that account for social, economic and environmental future implications, i.e. the three dimensions of sustainability, still needs to be determined. However, research showed repetitively that the stable functioning of the Earth system is a necessity for a successful global society in terms of social well-being and economic development (already explained in section 1.1 and illustrated in Figure 1 - Griggs *et al.*, 2013). Environmental sustainability should thus be prioritized in the development of aquaculture growth policies, as it is a prerequisite for the two other

dimensions' to be fulfilled. In this regard, this PhD project focused on the environmental sustainability of the aquaculture sector in the context of the implementation of new national policies, which is an underresearched topic that far.

1.4 HOW TO ASSESS ENVIRONMENTAL SUSTAINABILITY OF AQUACULTURE POLICIES

Studies have claimed that seafood is among the most environmental-friendly source of animal protein (Hall et al., 2011; Hilborn et al., 2018). However, other authors obtained results that are more nuanced. For instance, Clark and Tilman (2017) conducted a comparative analysis of the environmental impacts of multiple food production systems and concluded that when it comes to climate change impacts, seafood has in general slightly higher impacts than pork and poultry and lower to equivalent impacts than beef depending on which technology is used. Indeed, while production systems of e.g. poultry or ruminants are roughly similar globally, seafood can be produced using very different technologies. First, as raised in section 1.2, seafood can be caught or farmed. No other animal that is intensively consumed today is commonly caught/hunted to meet a large demand. Secondly, there are great differences within fisheries or aquaculture production systems. From small boats with hand-casting nets to gigantic fleets of trawlers, large variations in terms of sizes and technologies are observed in the wild capture industry. Aquaculture production is even more diverse, with systems that can be offshore or onshore, using mono- or polyculture (i.e. one vs. multiple species reared together), in open or closed environments (i.e. directly interacting with wildlife or not), in recirculating or flow-through water systems (i.e. with water reused vs. discharged in nature when contaminated). The feed is also an important source of difference, through the level of optimization of its management, the selection of its ingredients and the techniques used to feed the animals.

All these differences imply different inputs, outputs and emissions per unit of food produced and thus potentially different environmental impacts. Indeed, environmental impacts are directly linked to the inputs/outputs/emissions of a system. For example, greenhouse gases (GHG) emissions are directly linked to climate change impacts. Therefore, it is legitimate to question the environmental equivalence of all seafood production systems without differentiation when it comes to their impacts, and whether it is meaningful to talk about environmental sustainability of seafood in general.

Seafood production has been associated with several environmental impacts by biologists and ecosystem experts. One of the main environmental issues linked to wild capture is that it removes marine resources from the environment. This removal can disturb the natural balance of marine ecosystems and have consequences on multiple species from various trophic levels (Martin, 2017; Pauly et al., 2002). Aquaculture also participates in this problem as an important part of aquafeed (i.e. feed used in aquaculture) is marine-

based and originates from capture fisheries (Naylor et al., 2009). Another problem linked to wild captures is its contribution to climate change through the use of vessels fueled with petroleum products (Avadí and Fréon, 2013). Again, fish farming contributes to this issue as farmers use boats and vessels to access their offshore site and because many technologies require energy during their farming stage, which often implies the use of petroleum products as well (e.g. local diesel generators or electricity from the grid in non-fully-renewable-grid countries). Aquaculture can contribute to eutrophication, due to the emissions of uneaten feed and feces during production in open offshore systems (David et al., 2009). Escapes of farmed specimens might have a negative influence on local biodiversity (De Silva et al., 2009; Diana, 2009). Finally, aquaculture production induces the use of natural resources that are therefore not available for other usage, such as water and land (Bostock et al., 2010).

The magnitude of these impacts varies depending on the technology, the species and the location, calling for more nuanced statements regarding environmental sustainability of seafood. It becomes clear that increasing aquaculture production might have negative impacts on the environment and that the environmental implications of new aquaculture growth policies must be assessed; the main research question of this PhD project hence emerges:

→ *How to assess the current and prospective environmental sustainability of aquaculture growth policies?*

While experts have highlighted the different potential effects of aquaculture in various environmental studies, a comprehensive list of these impacts needs to be quantified in a systematic way to allow a fair comparison of the different aquaculture production systems. A common tool to quantify environmental sustainability of products and systems is life cycle assessment (LCA). It can be used to define which of several options is the most environmental-friendly, or to determine hotspots along the life cycle of a product or service by identifying the substances/processes with the highest environmental impacts. These can be useful for decision-makers of all sorts, from product designers trying to reduce the environmental impacts of their company to policy-makers looking for environmentally sustainable solutions. This ISO-standardized methodology allows to quantify environmental impacts of goods or services over their whole life cycle (see section 3.1 and Figure 3), which includes, but is not limited to, extraction of raw materials, manufacturing, storage, distribution, transport, use and end-of-life (such as disposal or recycling - ISO, 2006b, 2006a). Another strength of LCA lays in the diversity of impacts that can be included in one study, which helps to avoid environmental burden shifting when an option is chosen over another. It can however not assess the absolute sustainability of a product, a service or a system, i.e. it can only determine if it is more or less sustainable than other solutions satisfying the same function.

From a regulation perspective, LCA has been listed as a recommended tool for conducting impact assessments in the development of new regulations and the refinement of existing ones by the European Commission in 2015 (European Commission, 2015a), and is thus part of the “Better regulation toolbox” of the EU since then (European Commission, 2015b). This endorses its relevance as a support tool for decision-making in general. To produce policies with higher chances of success than in the past, implications on sustainability should be anticipated using scientific-based assessments, especially on the environmental aspects. The obtained growth of aquaculture production will be a great asset in meeting global food demand in a sustainable way. In that context, LCA appears like an adapted methodology to assess the environmental impacts of aquaculture growth policies, and thus LCA was selected as the rightful tool to assess current and prospective environmental sustainability of aquaculture growth policies in this PhD project.

Chapter 2 RESEARCH OBJECTIVES

The main **research goal** of that PhD project was to address the question:

→ *How to assess the current and prospective environmental sustainability of aquaculture growth policies?* (**RG**)

I defined four main **research questions** to address the research goal of the PhD project:

- What are the main findings of past LCA studies assessing the environmental sustainability of aquaculture? (**RQ1**)
- How environmental sustainability of aquaculture has been assessed in the past LCA studies in terms of methodological choices, and are there needs for improvement? (**RQ2**)
- How can the evolution of national aquaculture sectors be modeled and foreseen when taking into account demand, supply (e.g. farming practices), trade and market mechanisms? (**RQ3**)
- How can the environmental sustainability performance of the aquaculture sector at national scale be assessed in a foresight perspective? (**RQ4**)

To answer research questions 1 and 2, I conducted a critical literature review, which led to two journal papers (Papers I and IIa) and one conference paper (Paper IIb – see Table 1). To answer research questions 3 and 4, I built a framework and developed associated methods and models to help policy-makers assess aquaculture growth policies by anticipating their environmental implications. This framework was tested on two case studies, Singapore and Norway, as a proof-of-concept. The case studies were chosen because of the willingness of these governments to increase aquaculture production in the coming decades and due to the intrinsically different profiles of their aquaculture sectors. This led to the writing of three publications (Papers III, IV and V), as illustrated in Table 1. Therefore, a total of five scientific articles and one conference proceeding were produced to support this PhD project. The structure of the dissertation with an overview of the corresponding research questions and articles is available in Table 1.

A glossary is available at the end of the manuscript with the definitions of technical and study-specific terms.

Table 1. Thesis outlook with sections and corresponding publications (available in Appendix) to address research questions (RQ) and research goal (RG).

Sections	Research questions	Publications
<i>Chapter 3 – Past LCAs on aquaculture</i>		
Section 3.2 – Lessons learned	RQ1	Paper I
Section 3.3 – Methodology	RQ2	Papers IIa,b
<i>Chapter 4 – Framework development</i>		
Sections 4.1, 4.2, 4.5 and 4.6 – Framework	RQ3&4 (theory)	Paper V
Section 4.3 – Micro-level LCA (section developed in details in another paper)	RQ4 (theory)	Paper IV
Section 4.4 – Scenarios development (section developed in details in another paper)	RQ3 (theory)	Paper III
<i>Chapter 5 – Proof-of-concept</i>		
Sections 5.1.1, 5.1.2, 5.1.5, 5.1.6 and 5.1.7 – Case study 1: Singapore	RQ3&4 (proof-of-concept)	Paper V
Section 5.1.3 – Micro-level LCA for Singapore (section developed in details in another paper)	RQ4 (proof-of-concept)	Paper IV
Section 5.1.4 – Scenarios development for Singapore (section developed in details in another paper)	RQ3 (proof-of-concept)	Paper III
Section 5.2 – Case study 2: Norway	RQ3&4 (proof-of-concept)	Paper V
<i>Chapter 6 – Relevance & operability of the framework</i>		
All sections	RG	Paper V

Chapter 3 STATUS OF LCA APPLICATION ON AQUACULTURE SYSTEMS

In this chapter, I address the first two research questions of this PhD thesis: “What are the main findings of past LCA studies assessing the environmental sustainability of aquaculture?” (RQ1) and “How environmental sustainability of aquaculture has been assessed in the past LCA studies in terms of methodological choices, and are there needs for improvement?” (RQ2).

In section 3.1, I introduce the LCA framework with a short description of each of its main phases. I then present the key results of a critical literature review of past LCA studies on aquaculture systems: section 3.2 summarizes the main findings and section 3.3 the choices in terms of LCA methodology. All recommendations and identified research needs are recalled in section 3.4.

3.1 THE LCA FRAMEWORK

The LCA framework includes four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation (Figure 2). During the first phase, the goal of the study and the object of the assessment are described. Then methodological choices are taken, stated and explained for full transparency and reproducibility of the study.

Figure 2: The four phases of life cycle assessment (EC, 2010).

During the LCI phase, all inputs and outputs of the system are collected and inventoried, for all life cycle stages. The resource usage and emissions to air, soil and water are aggregated as elementary flows (or inputs/outputs to the ecosphere) and energy usage and waste are summed up in “man-made” flows (or inputs/outputs to the technosphere, see Figure 3 - Hauschild, Rosenbaum and Olsen, 2018). These flows may contribute to one or several environmental impacts, which leads to the LCIA phase. Each flow is attributed to the impact categories it influences, and multiplied by a specific characterization factor that has been developed specifically for this impact category and

this flow (Rosenbaum et al., 2018). By adding up all characterized flows associated to one impact category, characterized scores are created for a variety of impact categories, e.g. climate change, eutrophication, acidification, particulate matter formation, water scarcity, mineral resource use, etc (Rosenbaum et al., 2018). These impact categories can contribute to one (or several) area(s) of protection (AoP), namely ecosystem quality, human health and resource depletion, also called the endpoint indicators or damage (Rosenbaum et al., 2018), obtained with some additional calculation steps.

Figure 3: Life cycle stages of a product or service (i.e. system) with its inputs/outputs to the ecosphere and technosphere.

3.2 WHAT CAN WE LEARN FROM PAST STUDIES?

In the past, LCA has been applied to aquaculture and aquafeed production systems in many studies. In this section, I present the results of a critical literature review conducted on 65 papers in terms of findings. First, an overview of the studies' scope is drawn to understand what has been assessed so far (section 3.2.1). Then, the two main findings that emerged from the review are developed in detail: the importance of feed (section 3.2.2) and the importance of technology and intensity (section 3.2.3). Finally, the potential of LCA as a decision-making tool is discussed based on how it has been used for such purpose in past studies (section 3.2.4).

This section is based on elements published in **Paper I**; all results are therefore sourced from that paper, which for readability reasons, is not referenced systematically.

3.2.1 What has been assessed so far

A systematic critical review of the existing literature led to the identification of 65 studies published prior to mid-2017 that applied LCA on aquaculture for food production and/or on aquafeed production systems and included at least two impact categories. The

analysis of the geographical scope of these studies highlighted an important discrepancy between the regions assessed in LCA and the repartition of the global aquaculture production. As shown in Figure 4, the biggest difference concerned Asia, as 90% of the global aquaculture production originates from this continent while only 24% of the selected studies assessed Asian systems. This called for more LCA studies on Asian aquaculture systems, as environmental sustainability of aquaculture cannot be tackled by only improving the environmental performance of systems that represent a minority of the global production mix.

Concerning technologies, a large panel of different types and intensities have been assessed and/or compared, including commercial farms and pilot ones, mono- and polyculture, and several culture environments. In general, past studies focused on the optimization or comparison of individual farms. Exceptions include Iribarren, Moreira and Feijoo (2010) who took a sectorial perspective to assess the environmental impacts of mussel cultivation in Spain, Henriksson *et al.* (2017) who conducted an analysis of country-representative production categories and put it in perspective with scenarios of future aquaculture development in Indonesia, and Seves *et al.* (2016) who compared different seafood options available on the Dutch market from a consumer perspective. The conclusions of these macro-scale studies brought useful information to decision-makers thanks to their comprehensive perspective. Therefore, more large-scale LCA studies should be conducted on aquaculture systems to provide science-based material for better environmental governance.

Figure 4: Differences in geographical distribution between life cycle assessment studies and actual production of farmed seafood worldwide in 2015 (data from global production extracted from FAO, 2018a). Adapted from Paper I.

Figure 5 illustrates the overall environmental performance of past studies, through the averaged impacts of six impact categories harmonized per ton of live-weight seafood. High variability was found between the studies due to differences in terms of technologies, feed, optimization, species and methodological choices within studies. This confirmed that aggregated numbers from meta-analyses should be used with care when

e.g. talking about general impacts of aquaculture or comparing impacts of this production sector to other sectors. Additionally, the large variation within studies supported the need for producing assessments of all types of systems, including those barely assessed before such as underresearched continents, technologies or species.

Figure 5: Impacts per ton of live-weight seafood for six selected impact categories (from 140 cases out of 179, which communicated usable fraction and quantitative impact results). Midline is the median; box plots indicate the first and third quartile; whiskers indicate the maximum and the minimum values retrieved. Excerpt from Paper I.

3.2.2 The importance of feed

A recurrent finding across the assessed studies was the domination of feed production. It was found to be the key driver of several common impact categories assessed in LCA, such as climate change (found dominant in 56% of the studies), cumulative energy demand (found dominant in 58% of the studies), and acidification (found dominant in 63% of the studies). Two characteristics were found to influence generally the environmental impacts of feed: the feed conversion ratio (FCR) and the choice of ingredients.

The FCR reflects the mass of aquafeed needed per unit of live-weight mass gained by the specimen during growth. Therefore, the higher the FCR, the higher the quantity of aquafeed required per unit of seafood produced, and thus the higher the environmental impacts linked to the feed production due to this extra aquafeed. There are several possibilities to reduce the FCR, such as improving the feed management, i.e. the way the

feed is distributed to the animal in terms of frequency, quantity and schedules, or by choosing diets that are more adapted to the farmed species, e.g. by having higher digestibility.

The choice of ingredients influences the environmental impacts of feed because different ingredients are associated to different impacts. This is due to the variety of resources needed and manufacturing techniques used for the different ingredients. For instance, the production of marine-based ingredients, usually fishmeal and fish oil (FMFO) or raw fresh fish, increases the pressure on fish stocks due to the need for fresh fish from capture fisheries. This environmental impact is not included in common LCIA methods yet, and additional environmental indicators specially adapted to aquaculture or agriculture systems have often been added to the default impact assessment methods to fill that gap. Several impact indicators have been developed to quantify that issue, e.g. the maximum sustainable yield that assesses the pressure of capture on fish stocks through mortality and biomass unbalance. But the most commonly used is the net primary production use (NPPU), developed by Papatryphon *et al.* (2004). This environmental indicator quantifies the quantity of biotic resources that is not available for other purposes anymore. One advantage of this specific category is that it does not assess solely the use of marine resources but also the use of biotic resources from land-based ingredients, even though impacts of these are usually lower than FMFO. Land-based ingredients are however associated to other impacts, such as intensive water and land use due to the agriculture phase of the production (see e.g. Boissy *et al.*, 2011). Manufacturing the raw materials (e.g. wheat, soybean or rice) may require important energy inputs explaining why these ingredients can also have non-negligible impacts on climate change, energy use and acidification. Therefore, the choice of ingredients is crucial to reduce the environmental impacts of feed. Several approaches are available to that purpose.

One of them is to optimize the production of commonly used ingredients to reduce specific impacts. For instance, by replacing fresh fish in the production of FMFO by trimmings, the NPPU of marine-based ingredients can be decreased. Another one consists of decreasing the proportion of marine-based ingredients and replacing them by land-based ingredients with similar protein content, such as soybean meal. However, plant-based ingredients are not all equivalent in terms of environmental impacts and there is a risk of environmental trade-offs between different impacts (see e.g. Pelletier and Tyedmers, 2007).

Another possibility is the introduction of new ingredients with lower environmental impacts. A handful of LCAs have focused on comparing different aquafeed ingredients and some of the most promising ones are insect-based meal, algae-based meal and oil, and food waste from the food industry. Waste from human food production and consumption is found to have lower impacts on climate change, energy consumption and water use (Figure 6). Among the insect-based feed, black-fly-larvae-based aquafeed seems promising to reduce impacts on climate change and acidification, as well as human

toxicity, marine aquatic ecotoxicity and abiotic depletion, but has been found to have higher energy demand than FMFO (Figure 6). However, changing the ingredients in an established fish diet can influence the FCR negatively, i.e. increasing the amount of feed needed for the same weight gain due to differences in nutrients content or digestibility. Therefore, potential options for reducing the impacts of feed need to be considered with care and assessed over the whole life cycle.

To conclude, the review highlighted the dominance of feed production in the environmental impacts of aquaculture and several solutions aiming at decreasing the impacts of feed have been assessed. However, none of these feed options appeared as intrinsically better than the others due to the risk of environmental trade-offs. Thus, promising possibilities for reducing the environmental impacts of feed should be further investigated, including their influence on FCR, to determine case-to-case which solutions are the most environmental-friendly.

Figure 6: Ratio of the environmental impacts of conventional diet (Conv.) compared to those of different feed diets for seven selected impacts categories. Excerpt from Paper I.

3.2.3 The importance of technology and intensity

The technology type and intensity of production systems were also found to influence the environmental impacts. From the analysis of selected studies, it seemed that systems that are more intensive had higher impacts on global impact categories (i.e. climate change, acidification, energy use) but equivalent to lower impacts on regional and local impact categories (such as eutrophication and water use) than systems of lower intensity. There is therefore a risk of environmental burden-shifting when changing from low to high-intensity systems, which is often the case when more modern systems are implemented.

Another potential burden-shifting can occur when transitioning from open to closed technologies. Historically, one of the most criticized environmental impacts of aquaculture production is the escapes of farmed specimens (Diana, 2009). When the escapees are from a non-local species, it can disturb the natural balance of local biodiversity, and if the escapees are from a local species, there are usually genetic differences between farmed and wild specimens that can engender changes in the genes of the next generations of wild specimens and finally disturb the local diversity balance as well. This issue is only associated to open systems, such as cages/nets in the sea or lakes. Novel technologies are therefore often designed to prevent such problems by closing the production system, e.g. production on land in tanks supplied through a water recirculating system (i.e. recirculating aquaculture system - RAS), reproducing artificially the naturally occurring characteristics of open water environments. These systems are also associated with lower eutrophication impacts due to the absence of nutrients emission from uneaten feed and feces as in cages/nets. The drawback of these innovative systems is the increased need for energy required to imitate conditions that were natural in the traditional open systems, hence inducing an increase of different environmental impacts depending on the energy source used.

Finally, the variety of specimens reared together has been found to influence the impacts as well. Aquaculture production can be either monoculture (i.e. only one species produced) or polyculture (i.e. two or more species produced in the same tanks/nets/cages). While some studies could not conclude on the superiority of either of these two options, some others found that if the species grown together were selected wisely, polyculture could present environmental advantages compared to the same species grown separately in monoculture. For maximum benefits, the species grown together need to have different feeding habits so that they can feed on each other's by-products, which is often possible when different taxa are combined.

These findings support again the need for differentiating impacts of different technology types and species groups. Some opportunities to reduce specific environmental impacts have been highlighted, e.g. RAS for eutrophication reduction, but their superiority still needs to be confirmed and the potential environmental trade-offs they are associated to need to be addressed.

Figure 7: Ratios of the environmental impacts of intensive aquaculture systems over those of either semi-intensive or extensive aquaculture systems. Each dots represents a ratio found in a study. The crosses represent the average and the whiskers the standard error. Note the logarithmic scale on the y-axis. A ratio higher (lower) than 1 means that the intensive system has higher (lower) environmental impacts than the system with other intensity. Excerpt from Paper I.

3.2.4 LCA potential as a decision-making tool

As illustrated in the previous sections, LCA is useful to identify environmental hotspots of aquaculture and aquafeed production systems, as well as to compare different systems to determine the option with the lower environmental impacts. Used at the level of individual farms, as in most past studies, it can be used to determine how to improve already existing systems, to optimize new ones, or to identify the most environmental-friendly option(s) in a specific setting.

Macro-level LCAs, such as industry, sector or national level ones, are especially valuable for policy-making. They can be used to assess the validity of existing regulations or the potential consequences of new ones. Whether consumption- or production-oriented, large-scale LCAs can give information to decision-makers but also consumers. For example, consumption-based LCAs can be used to create eco-labeling for all products sold in a region, which helps consumers to choose products with lower environmental impacts. It can therefore be used to encourage more sustainable diets at a larger scale. Production-based LCAs can be used to give an overview of the environmental performance of a country production's facilities, and therefore potentially help to define opportunities of environmental improvement of a specific sector in that country, for instance by highlighting which sub-sector dominates the environmental impacts.

The review allowed retrieving 10 studies published before mid-2017 that could be qualified as large-scale LCAs due to their country or sectorial perspective. Among them, only three included the entire seafood sector without focusing their analysis on one species in particular. The review also identified two studies that conducted a prospective assessment, with overall only one gathering these two characteristics (Henriksson et al., 2017). More details regarding the scope and findings of past large-scale LCAs are

available in **Paper I**. A succinct review of the literature published between mid-2017 and January 2020 revealed that national and sectorial LCA studies on aquaculture are still scarce and their amount did not substantially increase since the literature review was conducted (only a few new studies were found, among which Henriksson *et al.* 2018 and 2019). Considering the various valuable information that these studies can produce for decision-makers, more LCA studies should be conducted on large systems and future production, and especially combining both aspects.

3.3 PAST METHODOLOGICAL PRACTICES AND LIMITATIONS

In this section, I present the results of the critical literature review in terms of LCA methodology. It emphasizes five methodological issues that were selected based on their high importance for the LCA results. After giving a short definition of the concept, the problem witnessed in the reviewed studies is exposed and recommendations to future LCA practitioners are produced using the ISO standards, which will potentially improve the reliability and consistency of their studies.

This section is based on elements published in **Papers IIa** and **IIb**; all results are therefore sourced from these papers, which for readability reasons, are not referenced systematically.

3.3.1 Defining a functional unit that reflects the assessed function

The functional unit (FU) defines a reference function based on which the environmental impacts are quantified. It should correspond to the main function of the good/service/system assessed and should answer the questions “what?”, “how much?”, “for how long/how many times?”, “where” and “how well?” (Hauschild *et al.*, 2018). The FU is one of the most important methodological steps of an LCA, especially for comparative studies as it ensures a fair and realistic comparison of goods and services.

The majority of the assessed LCA studies on aquaculture systems used an FU based on a mass of live-weight seafood (70% - see Figure 8). This is typical of production-oriented LCAs as it assesses a function based on the needs and benefits of the producer. The rest chose FUs based on processed/packaged product or edible mass of seafood, which reflected a consumer approach. The choice of FU is especially important for comparative LCAs, because it can change the final ranking of the assessed options, as proven e.g. in Cashion *et al.* (2016). It is therefore crucial to adopt a perspective that truly reflects the function that the practitioner wants to assess, and when it comes to food production systems this function is often linked to the nutritional needs of the consumers. Indeed, most studies that used an FU based on a live-weight mass of seafood actually described a consumer perspective in their goal definition. Therefore, the choice of their FU was inconsistent as it was not reflective of the intended function of the study. In general, food production LCAs should prioritize FUs based on a mass of edible product, on

recommended consumers' portions or nutritional characteristics such as protein mass or calories (already defended by Sala *et al.*, 2017 and Sonesson *et al.*, 2017). Comparing complete diets should be preferred when possible.

Figure 8: Distributions of the 65 reviewed LCA studies (a) between the different types of functional units (FU) for aquaculture and aquafeed and (b) between the different methods for handling multifunctionality, and (c) proportion of the assessments covering some key impact categories. NPPU=Net primary production use; BRU=Biotic resource use¹. Excerpt from Paper IIa.

3.3.2 Having a comprehensive life cycle coverage

The life cycle of aquaculture production systems contains several elements, which can be grouped like in Figure 9 in: feed production, energy production, infrastructures and equipment, production and usage of chemicals (or consumables), seafood farming and post-farming stages. Among the reviewed studies, 69% did not include any post-farming element, conducting therefore a so-called “cradle-to-farm-gate” study. Moreover, only 64% and 60% of the selected studies included chemicals and infrastructures/equipment, respectively. The most common reason raised by the authors for not including these elements was that they expected their impacts to be negligible. However, to avoid burden shifting between impact categories or between life cycle stages, a comprehensive life cycle coverage should be applied, i.e. the inclusion of all elements of the system. Indeed, the life cycle stages that are often neglected, such as post-farming, chemical usage and infrastructures/equipment, have been found to have great importance on the results in several studies. For instance in Seves *et al.* (2016) and Winther *et al.* (2009), post-farming

¹ Indicator similar to NPPU.

elements such as transport and distribution were found to change the final scores of climate change greatly, and therefore the ranking between the options assessed. In the assessed studies, 78% and 84% of the studies that included chemical usage and infrastructures/equipment, respectively, found that these stages had a non-negligible contribution in at least one impact category (defined as a contribution of at least 5%). Several past critical reviews already highlighted the importance of including all life cycle stages of aquaculture production systems (Henriksson et al., 2012; Parker, 2012), but this recommendation was not followed more often in subsequent LCA studies. Therefore, I reiterate to recommend that all life cycle stages should be included, in particular, chemical use, infrastructures/equipment and post-farming stages.

Figure 9: Different stages and processes of aquaculture production and types of system boundaries. The thick arrows represent the stages between which transport can occur (depending on the case study). Excerpt from Paper IIa.

3.3.3 Handling multifunctionality according to the ISO standards

Multifunctionality is a common methodological issue to tackle in LCA. When a process produces multiple goods or services and only one of these should be accounted for in the calculations of the final impacts, the LCA practitioner needs to choose how to “split the impacts”, i.e. how to handle the multifunctionality. The ISO standards have specific recommendations for this situation, with a hierarchy of methodological choices as following (ISO, 2006a, 2006b): (i) sub-division of the system, ; (ii) expansion of the system with the production of avoided goods/services corresponding to the co-functions; and (iii) allocation of the impacts based on a chosen allocation key, in which

case physical characteristics should be prioritized over economic ones. As seen in Figure 8, within the reviewed studies 58% used allocation, 13% system expansion and 3% both. The last 26% of the studies did not explicitly state which methodological choice was taken to handle multifunctionality, which is especially troublesome as this methodological choice was found to be of great importance for LCA results by all studies that included this aspect in their sensitivity analysis (Aubin *et al.*, 2015; Jonell and Henriksson, 2015; Kluts *et al.*, 2012; McGrath *et al.*, 2015; Medeiros *et al.*, 2017; Nhu *et al.*, 2016; Wilfart *et al.*, 2013; Winther *et al.*, 2009). Among the studies that used allocation, some argued that it was not possible to use system expansion because the function of the co-products could not be produced by other systems equivalently. For instance, fish oil cannot be produced in any other way than combined with fishmeal, and several authors argued that it could not reasonably be replaced by other oils due to its unique nutritional characteristics. This argumentation is legitimate in an LCA, but often, such discussion was missing and the choice of allocation (and in particular economic allocation as in 20% of the studies - Figure 8) seemed to be a default choice in the reviewed studies. A lack of consensus concerning the handling of multifunctionality has already been highlighted by Ayer *et al.* (2007). Therefore, there is a need for future LCA practitioners to follow the ISO standards more rigorously and to argument more precisely their decisions concerning multifunctionality handling, whatever these are.

3.3.4 Including all relevant impact categories

In the LCA studies included in the review, climate change, aquatic eutrophication, cumulative energy use and acidification were commonly assessed, but all the other impact categories were rarely included. In general, the choice of the included impacts was poorly justified with the only argument being that previous LCA studies on aquaculture assessed the same impacts. This is problematic because the environmental coverage of the impact categories included in an LCA study is crucial for the results. Neglecting environmental impacts that are affected by the assessed system can lead to burden-shifting or omission of crucial perspectives in the discussion. For instance toxicity, water use and land use impacts are of high importance for food production systems, as proved e.g. in Bosma, Anh and Potting (2011) or Kluts *et al.* (2012). Furthermore, some impact categories have been developed especially for food production, such as NPPU (see section 3.2.2), and are therefore especially important to include (using e.g. the method developed by Papatryphon *et al.*, 2004). Therefore, not only should all commonly assessed impact categories be included, but also toxicity impacts and resource depletion ones, such as water, land and biotic use.

Additionally, a research gap was identified, which concerns missing impact pathways. Despite the recent developments of LCIA methods (e.g. spatial differentiation in IMPACT World+ by Bulle *et al.*, 2019), several studies pointed out the lack of available impact pathways developed for some issues specific to aquaculture. Among these, the following two are highlighted due to their specific importance for ecosystems and human health: (1) the problem linked to escapes of farmed specimens and (2) the impacts of

antimicrobials usage on human health through antimicrobial resistance. For the first one, there is a need for the development of a new impact category that could be included in common LCIA methods. The second one might be solved by either including the impacts of antimicrobials similarly to chemicals, in methods such as USEtox (Bijster et al., 2017), or to combine LCA with risk assessment (RA – see section 6.3.1).

3.3.5 Critical interpretation of the results

Among the selected studies, only 49% conducted a sensitivity analysis and 28% a quantitative uncertainty analysis. Additionally, only half of the studies critically discussed the quality of their data. Overall, there was little critical discussion around the interpretation of the results. This could lead to the misuse of the results due to a lack of perspective of the reader on the potential limitations of the study read. In the interpretation phase of the LCA, both a sensitivity and an uncertainty analysis are recommended. While the former allows identifying parameters that have an influence on the LCIA results, the latter is crucial to identify uncertainty sources and thereby discuss the uncertainty level of the final results. This allows highlighting the study's limitations and prevents the misuse of the conclusions. While quantitative sensitivity analyses are feasible in all studies and do not require additional knowledge from the practitioner, quantitative uncertainty analyses are complex to conduct, and require specific software, adapted background data and additional information regarding all inputs of the foreground system. Therefore, in some cases, it is not possible to conduct a trustworthy quantitative uncertainty analysis. In these cases, a qualitative uncertainty analysis can be conducted instead. Based on this evidence, systematic quantitative sensitivity and qualitative uncertainty analyses should be conducted in future LCA studies on aquaculture, and a critical discussion on the quality of the data should be included.

An analysis of the data quality of past LCA studies highlighted another research need: the lack of shared LCIs. There is a need for more LCIs on Asian systems, to improve the assessment of this continent in particular. There is also a need for LCIs of low-income countries. Finally, there is a lack of LCIs regarding some life cycle stages, such as post-farming and consumption. All these should be addressed by the creation and inclusion of LCIs on aquaculture of all continents, all technologies, all species and all life cycle stages in commonly used databases (e.g. ecoinvent or Agri-footprint - Wernet *et al.*, 2016; Durlinger *et al.*, 2017)

3.4 SUMMARY OF THE IDENTIFIED RECOMMENDATIONS AND RESEARCH NEEDS

To summarize, the following recommendations and research needs emerged from the analysis of the past LCA studies on aquaculture systems, which might improve the quality and reproducibility of new LCAs on aquaculture.

About the type of applications:

- Assessing systems that have barely been assessed so far, such as underresearched continents, technologies or species.
- Conducting LCA studies on large-scale systems and future production, and the combination of both aspects.
- Investigating further how to reduce the environmental impacts of feed.
- Differentiating between different technology types and species groups.

About the LCA methodological steps:

- Defining FUs that truly assess the functions studied, and therefore if the study is based on consumption, prioritizing FU based on edible mass, nutritional characteristics or complete diets.
- Having a full life cycle coverage, including infrastructure/equipment, chemicals use and post-farming.
- Following rigorously the ISO standards for multifunctionality handling.
- Having a broad impact coverage.
- Developing new impact pathways, to allow assessing e.g. impacts of escapees or antimicrobial resistance.
- Discussing critically the LCA results in light of the data quality and including sensitivity and uncertainty analyses.
- Building and sharing LCIs of aquaculture systems from all continents, for all life cycle stages and for diversified systems.
- Improving the transparency regarding data and methodological choices.
- Always discussing and explaining important methodological choices (e.g. multifunctionality handling and FU definition).

Chapter 4 FRAMEWORK TO ASSESS FUTURE ENVIRONMENTAL IMPACTS OF AQUACULTURE POLICIES

In this chapter, I address the theoretical aspects of the two last research questions of this PhD thesis: “How can the evolution of national aquaculture sectors be modeled and foreseen when taking into account demand, supply (e.g. farming practices), trade and market mechanisms?” (RQ3) and “How can the environmental sustainability performance of the aquaculture sector at national scale be assessed in a foresight perspective?” (RQ4).

To that purpose, and based on the research needs identified in Chapters 1 and 2 and the recommendations identified in Chapter 3, I constructed a theoretical framework to assess the environmental impacts of new aquaculture growth policies at national level using LCA and based on scenarios with minimum economic viability. The framework is intended to be used by various aquaculture stakeholders, hereafter referred to as “practitioners”.

Except explicitly stated otherwise, this chapter is based on elements from **Paper V**; therefore, for readability reasons, the paper is not referenced systematically.

4.1 A FLEXIBLE EX-ANTE FRAMEWORK TO ASSESS AQUACULTURE POLICIES

The general structure of the framework developed in this PhD project is presented in Figure 10. It is composed of four steps. A practitioner willing to use the framework would already have a specific country $\mathcal{A}$ and policy P in mind (e.g. the National Aquaculture Development Strategy and Action Plan of Bangladesh for 2013-2020), which would result in an associated period Y_1 - Y_2 during which the policy is implemented (e.g. 2013-2020 for Bangladesh). The period can be chosen longer than the expected implementation of the policy to observe the legislation’s consequences (e.g. 2010-2030 for Bangladesh). Therefore, these three elements are defined as the object of the assessment. As they are the core of the study, they should be specified clearly before beginning to follow the four main steps of the framework.

Figure 10: General overview of the framework developed in this thesis. The six main life cycle stages to consider are underlined in step 3. Excerpt from Paper V.

The first step aims at getting a detailed overview of the current and future seafood industry in country A in terms of farmed species, technologies used and quantities produced. It corresponds to the scoping of the assessment. Wild fisheries and aquaculture should both be considered in this step, as it will feed the economic model (step 2) that should include all seafood production sources (see section 4.4). The concrete

output of this step is a list of production categories S_iT_j , defined by a species group S_i and a technology type T_j , and their corresponding production quantities in country A at the beginning of the period (i.e. usually in Y_1). Then, the practitioner can choose to conduct an optional step O, which consists of a micro-level LCA aiming at comparing the environmental impacts of the different production categories S_iT_j and identifying hotspots in their life cycle. In the case where aquaculture in country A has been intensively assessed with LCA in the past, this step is not necessary because the practitioner can gain an overview of the environmental impacts of the different systems from the literature. Contrarily, this step is especially relevant if the environmental impacts of aquaculture in country A were never assessed before, as it additionally produces LCIs that can be used by other LCA practitioners. In step 2, an economic demand-supply equilibrium model is adapted to build scenarios $S_{\ell k}$ of seafood production development in country A during the period Y_1 - Y_2 , differentiated by production categories (i.e. S_iT_j). These scenarios should be based on policy P and can be used to assess the different economic consequences of the policy implementation but also to challenge the practical economic feasibility of policy P . There is the possibility to include social and environmental considerations in these models and to define thresholds on these features. For example, the annual aquafeed consumption of the aquaculture sector can be quantified by associating each production system to a specific FCR and limiting the feed consumption to a maximum annual quantity thanks to an additional constraint or equation. However, these already complex models become easily unstable when more parameters are implemented, and only inventory level parameters can be assessed. So currently, such models do not have the possibility to include an environmental impact module, hence the need for an ex-ante environmental sustainability assessment such as an LCA. To that purpose, a macro-scale LCA is conducted in step 3 to assess the environmental impacts of aquaculture production per mass of edible seafood produced for each scenario $S_{\ell k}$ and its evolution over the period Y_1 - Y_2 . If step O was conducted, the data collected for that step are used again in step 3, even though different methodological choices can be adopted. Step 4 corresponds to the interpretations of the results obtained in step 3.

Each of these steps is described in detail in the following sections of this chapter.

4.2 DESCRIBING THE SEAFOOD PRODUCTION INDUSTRY (STEP 1)

For this first step, the practitioner should review all documentation linked to the seafood industry of country A , including statistical data from national institutions, reports and speeches from the government and the industry, scientific literature and other potential sources (e.g. newspapers articles). This should lead to a rigorous description of the seafood production sector, including (i) which species are produced (if numerous species

are produced, the practitioner should identify groups of species by types such as crustaceans, marine fishes or mollusks), and in which proportions; (ii) which technologies are currently used to produce these species (or groups of species) or new ones; and (iii) which new technologies are likely to be developed in the future to produce these species (or groups of species). The output of this step is a list of species or groups of species, with current production distribution, and linked with the main technologies currently and prospectively used to produce them.

4.3 MICRO-SCALE LCA OF AQUACULTURE PRODUCTION CATEGORIES (STEP O)

This section is based on elements from **Paper IV**; therefore, for readability reasons, the paper is not referenced systematically.

If aquaculture in country $\mathcal{A}$ has not been assessed comprehensively in the past, it is recommended to conduct a preliminary environmental sustainability assessment of the different production categories identified in step 1 before conducting the macro-scale LCA study (i.e. the goal of this framework). Overall, the same data are needed than for the macro-scale LCA, and therefore conducting step O does not add any workload in this field. However, the two LCAs have different purposes; the micro-scale one aims at comparing the environmental performance of several aquaculture production systems, while the macro-scale one intends to compare the environmental impacts of scenarios of aquaculture development that comprises the above-mentioned systems. Therefore, some methodological choices are different.

4.3.1 Goal and scope definition

The goal of this LCA study is to (i) compare the different production systems identified in country $\mathcal{A}$ in terms of environmental impacts, and (ii) identify the stages of their life cycle that are associated to the highest environmental impacts to highlight environmental improvement potentials. The study can assess only the present situation (corresponding to the data collected, or year Y_1), but a prospective approach can be added by assessing other years of the time scope as well, e.g. the last year of the period i.e. Y_2 . The rest of this section considers that two years are assessed, which are the first and the last years of the time-scope (Y_1 and Y_2).

An FU adapted for the micro-scale study is “the average production of 1 ton of edible seafood in country $\mathcal{A}$ ”. As illustrated in Figure 10, the system boundary should include six main elements: the fingerlings production (usually happening in another company/facility than the grow-out farm), the feed production, the infrastructures and equipment, the consumables (e.g. oxygen and cleaning products), the farming stage (also referred to as production stage and including energy and water usage, direct emissions happening during the production, and avoided products) and the post-farming stage. The

whole life cycle of each of these elements should be considered (i.e. from the extraction of raw materials to the end-of-life). According to the ILCD Handbook definition, the micro-scale nature of the study calls for a decision-context A and therefore an attributional modeling (EC, 2010), which implies the use of average data. The ISO 14044 standards should be followed for the handling of multifunctionality to attribute impacts to the different functions produced: system expansion should be prioritized, then allocation based on physical characteristics, and lastly, economic allocation, if it is the only applicable method (ISO, 2006a, 2006b).

4.3.2 Building country-representative inventories

To meet the requirements of the study, the LCIs of the different production categories should be (i) country-representative and (ii) time-differentiated between Y_1 and Y_2 .

Country-representativeness

To build country-representative LCIs, the preferable approach is to collect primary data in as many individual farms as possible, preferably all farms of country $\mathcal{A}$. All production categories Stj should be covered. The best practice is to visit the farms in person and interview the farmers in order to collect comprehensive data for the LCA, i.e. all inputs and outputs of the farming system. As part of this PhD project, a standard questionnaire was developed to assist the practitioners during the farmers' interviews and ensure that all important aspects of the production are covered (available in Appendix 1). A standard table was also developed to help the practitioners to have a comprehensive overview of the data needed to conduct an LCA study of an aquaculture farm (available in Appendix 2). Another way to obtain primary data is to send the developed questionnaire and/or table to the farmers to be filled without the presence of the practitioner. This option might lead to a lack of details in the information collected, depending on the understanding of the questions by the farmer. To avoid that situation, the questionnaire/table needs extra side explanations to ensure a comprehensive communication of the data from the farmer to the practitioner. The experience gained during this project led to conclude that it is more efficient to meet the farmers in person, as the other solution often leads to multiple rounds of questions until all information is collected, but it might not be possible in all cases due to lack of time or geographical restrictions.

Once the data is collected, it needs to be aggregated in order to reflect the entire production of the country. In the case where all farms have been visited and included in the data collection, a simple average of the data weighted by the yearly production of each farm produces country-representative LCIs. In the case where not all farms could be visited (e.g. due to time, geographical or budget restriction, or because not all farmers agreed to participate to the study), the practitioner should decide which farms are representative, based on its own knowledge, the literature and preferably the expert opinion of aquaculture stakeholders of country $\mathcal{A}$, and potentially remove production systems or data that are considered as too atypical. It is necessary to gauge the quality of

each single input/output collected to determine if it can be used to build the country-representative LCIs, because erroneous data could have been collected due to e.g. misunderstandings between the farmer and the practitioner. The data selected is then aggregated based on the annual production of each farm, for each production category. If a primary data collection is not conceivable (e.g. due to strict time, geographical or budget restrictions, or total refusal of all farmers to participate in the study), the inventories can be built based on existing literature. This requires that LCA studies have already been conducted on country A .

Time-differentiation

The LCIs built above correspond to the current practice (i.e. year Y_1), and needs to be adapted to the future year Y_2 for the prospective part of the study. The different factors, parameters and processes that are likely to evolve through time need to be identified. For instance, aquaculture production systems, as all other technology-based systems, are likely to become more optimized with time. This can be reflected by a decrease in water or energy use, or a general increase in productivity. Another factor that is likely to change is the feed use. New ingredients are likely to be introduced, FCR is likely to change (linked to e.g. technological optimization), or the way commonly used ingredients are produced is likely to change. Therefore, the practitioner needs to select all factors, parameters or processes that are considered likely to change through the period Y_1 - Y_2 , together with the expected degree of change (e.g. -10% between Y_1 and Y_2 , or multiplied by 2 at the mid-period compared to Y_1). These changes should preferably be based on literature or expert opinions (its own or other aquaculture stakeholders' one).

4.3.3 Life cycle impact assessment

As recommended in the ISO standards and highlighted in the literature review (section 3.3.4), an extensive set of impact categories should be included in the assessment. LCIA methods already available in LCA software can be used, such as ReCiPe 2016 or IMPACT World+ (Bulle et al., 2019; Huijbregts et al., 2016), which will ensure the diversity of the impact categories' selection. Additionally, including NPPU (Papatriphon et al., 2004) or other impact categories that assess the use of marine resources is recommended, according to the preference and convenience of the practitioner.

4.4 DEVELOPING SCENARIOS OF AQUACULTURE DEVELOPMENT (STEP 2)

This section is based on elements from **Paper III**; therefore, for readability reasons, the paper is not referenced systematically.

The structure of this step is presented in Figure 11 and consists of five sub-steps: (2.1) characterization of targets for future seafood production, based on governmental policies; (2.2) elaboration of the scenarios; (2.3) construction of the adapted Asiafish

model; (2.4) generation of the scenarios in Asiafish; and (2.5) analysis of the generated scenarios and assessment of the policy implications for the aquaculture production mix and from an economic perspective. Most of these sub-steps are sequential, requiring outputs from previous sub-steps (see Figure 11). The framework is meant to be an iterative process; thus, when reaching sub-step 2.5, the scenarios obtained should be analyzed critically and the practitioner should go back to previous sub-steps in case of unrealistic results or inconsistencies.

Figure 11: Structure of the framework for Step 2 and its five associated sub-steps (2.1 to 2.5) to assess national policies on seafood production future. Black arrows illustrate which outputs of previous sub-steps are necessary to conduct that particular sub-step; grey dotted arrows represent the iterative process, and the red arrow represents how policy analysis in step 2.5 might deliver potential recommendations to improve/adapt existing policies of step 2.1.

4.4.1 Characterizing targets based on governmental policies

Using the data collected in Step 1, all government communication should be analyzed thoroughly and the main policies and regulations concerning seafood production futures should be highlighted; this is step 2.1. This should be used to characterize targets in terms of aquaculture or capture fisheries development goals for the selected period (e.g. until 2040). These could be (i) an increase or decrease of production from specific technologies, or in total, (ii) the introduction of specific state-of-the-art (SOTA) technologies or new species, or (iii) new incentives to create more employment linked to that industry. Organizing meetings with local stakeholders within seafood production and regulations is highly recommended, to discuss the findings of the above-mentioned review, and obtain an expert opinion on the potential futures of aquaculture and capture fisheries in country *A*. Therefore, the defined targets should translate the communicated

government policies and regulations, and be based on the documents reviewed as well as expert opinions.

4.4.2 Defining scenarios

Based on the targets defined in Step 2.1, scenarios of aquaculture and fisheries development should be defined for the selected period (e.g. 2019-2030); this is the object of Step 2.2. Defining a business-as-usual scenario (BAU) is recommended, i.e. a scenario describing no drastic changes in the current and historical trends, as well as several other explorative scenarios. These scenarios need to be described in terms of yearly changes in production for the production categories identified in Step 1, each of them defined by a specific species group and technology type (e.g. mollusks produced on long lines). The change can be expressed as an increase or decrease in percentage, or as a target value in quantity or price. At that stage, the expected change may be described as a range of percentages or in general terms.

4.4.3 Adapting a demand-supply equilibrium model

Several demand-supply equilibrium models have been developed in the past to assess seafood production. The requirements of the framework implied that the demand-supply equilibrium model selected for this study fulfilled three criteria: (i) high level of disaggregation of the supply (i.e. differentiation between technologies and species according to the categories built in step 1), (ii) adequate accessibility and documentation of the model, and (iii) wide stakeholders' acceptance. A review of the literature revealed that the most commonly used models were the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model and the Asiafish model. Their popularity ensured that both models fulfilled the third criterion. The IMPACT model links economic, water and crop models and was developed by the International Food Policy Research Institute in the 1990s to help decision-makers assess policies targeting hunger and poverty reductions (Robinson et al., 2015). Its level of disaggregation in supply did not fit the requirements of this framework (first criteria). Additionally, this model was not publicly available and its access could not be obtained easily from the developing team, therefore not fulfilling the second criteria either. Consequently, this model was not selected for the framework.

The alternative model was Asiafish, developed by WorldFish in 2000 and described in Dey et al. (2005). This model focuses on seafood and fits the required level of disaggregation in terms of species and technologies, as it is a multi-product equilibrium model of fish supply, demand and trade with a possibility of high disaggregation in terms of markets, species and technologies (WorldFish, 2009). It was first developed to assess nine Asian countries, namely the Philippines, Thailand, China, Bangladesh, Sri Lanka, India, Indonesia, Vietnam and Malaysia, which resulted in multiple studies (e.g. on the demand for fish in the Philippines in Garcia, Dey and Navarez, 2005; on the effects of export prices on fish demand/supply in the Philippines in Rodriguez, Garcia and Navarez, 2005; on the fish demand in the above-cited nine countries in Dey *et al.*, 2008;

or on Indonesian production development in Tran *et al.*, 2017). The model was accessible by contacting the developing team, and came with adequate documentation. The Asiafish model met the three criteria, and was therefore selected for the framework.

Asiafish is built in three compartments: a consumer core, a producer core and a trade core (Dey *et al.*, 2005). The consumer core is a three-stage budgeting framework, with the first two stages estimated through the household demand and fish expenditure functions and the third stage estimated using the Almost Ideal Demand System (AIDS). The producer core uses the normalized quadratic profit function approach to estimate the quantities produced and their price in each category $S_i T_j$. The trade core uses seafood export supply and import demand functions imposing the Armington assumption to estimate the quantities and prices of imports and exports, i.e. assuming that goods from different regions are imperfect substitutes that can have different prices in different countries (Armington, 1969). The model is then solved by imposing the balance of supply and demand. The solution is obtained using the optimization software GAMS (Generalized Algebraic Modeling Solver - GAMS Development Corporation 25.0.3, 2019).

In the proposed framework, the Asiafish model is used to analyze the consequences of specific policies on seafood production while taking into account the complex mechanisms of demand and supply at country level. It is thus necessary to disaggregate the domestic supply (i.e. production in the country) in categories separated by species groups, but also by technology types (i.e. species group S_1 produced with technology type T_1 and species group S_1 produced with technology type T_2 being two different supply categories). However, consumers do not differentiate between equivalent products produced by different technologies at the demand level (e.g. same fish produced in farms or captured - Carlucci *et al.*, 2015). A more aggregated level of information is therefore needed in the demand core. The original model developed by Worldfish allows different levels of disaggregation for domestic supply and demand, but imports and exports need to be split using the highest level of disaggregation (whether it is the demand or supply – Figure 12). This means that in the original model, it is required to know what technology has been used in the production of exported and imported goods. These data are nearly impossible to find in practice; hence, the Asiafish model was adapted to allow for more disaggregated domestic supply than demand sources while having the lowest level of disaggregation at imports and exports level (Figure 12).

These changes implied that the number of equations in the model became inferior to the number of unknowns. To tackle that issue, equations that link producer prices of species produced using different technologies were added. Production costs vary depending on the technology used, and therefore it is likely that the producer price vary too. The additional equations are generically formulated in Eq. 1:

$$PP_{S_1T_1} = a_{S_1T_1T_2} * PP_{S_1T_2} \text{ (Eq.1)}$$

where $PP_{S_1T_1}$ is the producer price of category S_1T_1 , $PP_{S_1T_2}$ is the price of category S_1T_2 and $a_{S_1T_1T_2}$ is a multiplicative factor translating the price difference between the categories of S_1 produced with two different technologies. The factor “a” can be constant or vary through the years, evolving with the maturation of the technology.

Figure 12. Structure of the original Asiafish model (A) compared to the structure of the adapted Asiafish model (B). Excerpt from Paper III.

Asiafish becomes a multi-period model, which creates annual projections every time it optimizes with new parameters, when selected demand and supply shifters (such as population growth, inflation and technical factors) are differentiated by periods of time. These projections are not forecasts, and should therefore be used only to illustrate demand and supply potential trends in the future (Dey et al., 2005).

The model can be easily developed and adapted to become more comprehensive in terms of socioeconomic and environmental constraints of the country, for instance by enforcing new parameters, adding new thresholds on existing ones, or implementing new equations. This flexibility participates in making the model attractive to apply on multiple and diverse case studies.

In practice, in Step 2.3, the practitioner should collect the input data needed for the model, which includes (i) production, imports and exports data (in quantity and value), (ii) national data (or regional, depending on the needs of the study) such as population, expenditure patterns and average income, and (iii) economic data such as demand and expenditure elasticities differentiated by fish species or groups determined in Step 1. It is then needed to adapt the model in GAMS to fit the requirements of the targeted country in terms of disaggregation of the species and technologies. Finally, the data can be implemented in the Asiafish model.

4.4.4 Generating scenarios

The scenarios are generated by implementing changes over the years in the Asiafish model that reflect the change in policy. It is one of the model's assumptions that such change can be modeled as a change in production, due to a controlled difference between

the actual and the effective price as described theoretically by Alston et al. (1995). The effective price PE represents the effective quantity of an output provided by a given physical unit, and the actual price is the price at which the output is sold by the producers, i.e. the producer price PP. The ratio between the two in the Asiafish model is called the technological growth factor λ_{iy} , also described by Dey et al. (2005a) as the proportional change of output of supply QS_i due to technological progress or policy shift at year Y compared to the starting year of the model, which is expressed in Eq.2.

$$PE_{iy} = \lambda_{iy} * PP_{iy} \text{ (Eq.2)}$$

This influences the production of supply QS_i on year Y because prices and supply quantities are strongly linked through the other equations of the model. In order to generate the scenarios defined in Step 2.2, the practitioner needs to change the technological growth factors (i.e. λ_{iy}) according to the desired change in production (e.g. if 10% increase of S_iT_i is requested on year y , then set $\lambda_{S1T1y} = 1.1 * \lambda_{S1T1y-1}$). The process can be iterative, especially when the target production is in a long-term future.

The outputs of Step 2.4 are the technological growth factors defined for each scenario as well as the model's results over the whole period. The latest consists of the annual domestic production, consumption and trades expressed as their quantities and prices, over the entire period considered, disaggregated by species or groups of species and technologies. The terms “increase/decrease of the technological growth factors (i.e. λ_{iy}) of x% for production category S_iT_j ” and “increase/decrease of production for production category S_iT_j of x%” are equivalent.

It is important to mention that the complexity of the model and its important number of default constraints might lead to instabilities in the resolution. Boundaries are set to reflect the reality of the variables (e.g. prices should be strictly superior to 0,001 USD/kg) and if these boundaries cannot be respected anymore (e.g. negative prices), the tested growth is not feasible according to the current model. Therefore, not all sets of technological growth factors are viable for the model, and if the parameters λ_{iy} are set too high, the model cannot find an optimal solution over the period Y_1 - Y_2 and stops running. An iterative work of trials-and-errors is often needed to identify and refine λ_{iy} parameters that allow getting to the desired targets.

4.4.5 Analyzing the scenarios for policy implications

It is recommended to include four different tasks in sub-step 2.5, which are consistency check, analysis of policy implications, uncertainty/sensitivity analysis and final recommendations (see Figure 11).

The practitioner should begin by conducting a consistency check of the outputs of Step 2.4, looking for economical inconsistencies or potential errors in the script or in the input data. These inconsistencies should be corrected in case of errors, and alternative solutions

should be considered in case of economic incoherence (e.g. by using other data sources or changing the calculation methods). The choices made in the previous steps, such as assumptions and hypotheses, should be critically questioned in light of the model's outputs and changed or adapted if necessary (hence the iterative process, see Figure 11).

Then, the practitioner needs to analyze the obtained scenarios to assess if the implementation of the considered policy has the expected consequences on seafood production development (in relation to the goals of the policy). This consists of looking at the annual domestic production, consumption and trade quantities and prices, and compare them to the targets of the scenarios (defined in step 2.1). If the targets could not be reached in the model because it led to a collapse due to unfeasible optimization, the cause should be identified and treated before re-assessment of the model. For instance, input parameters can be adapted to improve the stability of the model, or if no other solution appears realistic, the objective of the study should be adapted. This analysis is specific to each case study, and should be adapted accordingly.

The limitations of the model should be considered and described so that the reader can put the results of the study in perspective. For this purpose, at least a qualitative uncertainty analysis should be conducted, in which all the sources of uncertainties are considered and ranked from the most to the least uncertain. Conducting a sensitivity analysis on the most uncertain parameters is highly recommended. A variation (e.g. more or less 10%) is applied to the selected parameters, and the model is computed again. The changes in consumption, production, imports and exports quantities should eventually be analyzed to assess how sensitive the results are to the different parameters.

Finally, recommendations should be delivered regarding which scenario(s) to prefer and how to implement the policy with higher chances of success, reflecting on the policy implications and the limitations of the study.

4.5 MACRO-SCALE LCA OF NATIONAL AQUACULTURE INDUSTRIES (STEP 3)

During this step, the practitioner conducts a macro-scale LCA of the entire aquaculture industry of country $\mathcal{A}$, comparing the environmental impacts of the different scenarios developed in step 2. It contributes to filling the lack of large-scale and prospective studies highlighted in the literature review (see section 3.2.4).

4.5.1 Goal and scope definition

The macro-scale study aims at comparing the evolution of the normalized environmental impacts through the period Y_1 - Y_2 of the different scenarios constructed in step 2. An adapted FU is “the average yearly production of 1 ton of edible seafood in country $\mathcal{A}$ during the period Y_1 - Y_2 ”. This FU reflects the evolution of the environmental eco-

efficiency of aquaculture production over the years depending on the scenario assessed, independently from the total quantity of seafood produced in that scenario (note however that when the impacts per FU increase, the eco-efficiency of the aquaculture sector decreases). The system boundary should include the same elements as the micro-scale study, which are illustrated in Figure 10. The large-scale perspective of the study implies that changes can potentially have structural consequences on other industries or systems, e.g. the meat production industry. In that context, the ILCD Handbook definition calls for a decision-context B, which entails a consequential modelling and therefore the use of long-term marginal data (EC, 2010).

Why this FU and not the total environmental impacts of the aquaculture industry?

It is tempting to look at the environmental impacts of the whole aquaculture industry in country $\mathcal{A}$ over a certain period (e.g. one year), but this approach raises important issues. Food is a physiological need and seafood is not the only product that can fulfill it. Therefore, total food demand per capita has a limited variation, especially in high-income countries where people have enough income to fulfill plainly their nutritional needs. The additional seafood production from the growth of the aquaculture sector is therefore likely to replace an already existing need that would otherwise have been covered by imported seafood or by other food, likely other protein-based products, but it does not create a new need. Based on the assumption that the main function of seafood is to fulfill nutritional needs, the total aquaculture production of country $\mathcal{A}$ in year Y does not fulfill the same function in the different scenarios because the total quantity produced varies within the scenarios. For instance, if in year Y the annual production of the aquaculture sector is 100 tons in scenario Sc_1 and 1000 tons in scenario Sc_2 , scenario Sc_1 will fulfill the nutritional needs of approximately 10 times fewer people than scenario Sc_2 . Therefore, adopting a pure producer approach by assessing the total impacts of an industry at national level and comparing it directly is very risky, as the conclusions drawn on this comparison might be misleading and non-adapted. Instead, a pure consumer approach should be preferred, assessing e.g. the total consumption of seafood or food in country $\mathcal{A}$ during the whole period of Y_1 - Y_2 , and therefore include (i) only the domestic production that goes to domestic consumption, (ii) the production of the seafood imported to cover domestic consumption and (iii) the production of other food items that are substitutable to seafood in some of the scenarios. This way, all options cover the same function. Additionally, scenarios with high total production quantities are likely to be “penalized” if comparing the total impacts of the aquaculture industry, i.e. present higher environmental impacts than scenarios with lower production quantities, although increasing the production is also crucial for a long-term sustainable seafood production sector (section 1.1). This topic is discussed further in section 5.3.3 and 6.3.3.

4.5.2 Building time-differentiated, country-representative inventories

In practice, the LCIs of the macro-scale study are built in two sub-steps:

1. Building country-representative LCIs of each production category $SiTj$ per average ton of edible seafood produced and for each year of the period Y_1 - Y_2 .
2. Combining them with the yearly production quantities expected in each scenario as a weighting to obtain the above-described FU.

The first step requires similar LCIs than step O, except for some methodological changes due to the consequential nature of the large-scale study. Therefore, for the data collection and the country-representativeness of the LCIs, the reader should refer to section 4.3.2. The time-differentiation is similar as well except that it is done for each year between Y_1 and Y_2 .

The second step is conducted by simply multiplying the impact scores obtained in the first step by the production mix obtained in each scenario for each year of the time-scope.

4.5.3 Life cycle impact assessment: the importance of a comprehensive coverage

Similarly to the micro-scale study, a large set of impact categories should be assessed to meet the recommendations from the literature review, including some specifically developed for food production systems (see section 4.3.3).

4.6 INTERPRETING THE OBTAINED RESULTS (STEP 4)

Once the LCA conducted, the results of the framework are produced. The practitioner can then observe which scenario is associated with the lowest environmental impacts per unit of average edible seafood produced, and observe potential trade-offs between impact categories. The interpretation should be done based on the FU assessed and account for the limitations of the study, especially in terms of uncertainty concerning the prospective part. As recommended in the literature review, at least a quantitative sensitivity analysis and qualitative uncertainty analysis should be conducted.

Based on these findings, the practitioner can produce recommendations to decision-makers and other aquaculture stakeholders of country $\mathcal{A}$. Based on an in-depth analysis of the scenarios obtained, the minimum macroeconomic viability of policy P can be assessed within the limits of the factors and theories included in the economic model. Combined with the environmental impact assessment, it allows identifying the scenario(s) that bring(s) the most benefits on economic and environmental aspects in the long-term. Thereby, these science-based assessments can be used by decision-makers to improve policy P or other aquaculture growth policies based on anticipated consequences.

They can be used to define which technologies and species should be prioritized and therefore encouraged in country $\mathcal{A}$, and which should be limited, depending on the goals of policy P and while limiting the environmental impacts of the aquaculture sector. To

reach the desired production mix (the one simulated in the theoretical scenarios of this study), local decision-makers can create incentives for current and new farmers that make some production systems more attractive than others. They can also implement regulations that limit the production from some technologies in a quantified way, e.g. implementing a maximum aquaculture production per geographical zone to limit specific regional environmental impacts such as eutrophication. The correct incentives and regulations have to be defined in detail by decision-makers themselves according to each countries' situation and governance possibilities, but they can be inspired by the results produced by this framework.

Chapter 5 CURRENT AND FUTURE ENVIRONMENTAL PERFORMANCE OF THE AQUACULTURE SECTORS IN SINGAPORE AND NORWAY

In this chapter, by applying the developed framework on two case studies, I address the practical aspects of the two last research questions of this PhD thesis: “How can the evolution of national aquaculture sectors be modeled and foreseen when taking into account demand, supply (e.g. farming practices), trade and market mechanisms?” (**RQ3**) and “How can the environmental sustainability performance of the aquaculture sector at national scale be assessed in a foresight perspective?” (**RQ4**).

Singapore was selected as first case study due to its newly announced aquaculture growth policy, my easy accessibility to primary data (thanks to my mandatory research stays in Singapore to fulfill the requirements of the Joint Program), and the need for more LCA studies on Asian systems (highlighted in the literature review, section 3.2.1). Norway was selected as a second case study due to its very contrasting profile in terms of aquaculture production compared to Singapore and the availability of comprehensive data in the literature. The two case studies are detailed and analyzed separately in sections 5.1 and 5.2, and common discussion topics are addressed in section 5.3.

This chapter is mainly based on elements from **Paper V**; except stated otherwise, all results are sourced from that paper, which for readability reasons, is not referenced systematically.

5.1 SINGAPORE – THE “30-BY-30” TARGET

5.1.1 Singapore willingness to increase seafood production

In 2012, a group of economists, researchers, country analysts, and food, climate and natural resource specialists gathered under The Economist Intelligence Unit and developed a national indicator to assess food security, named the Global Food Security Index. This index accounts for affordability, availability, quality and safety of food. In its last update in 2018, the indicator was applied to 113 countries around the world, and Singapore drastically stood out as it obtained the highest score in general, but ranked 109th in the Natural resources & resilience ranking (The Economist Group, 2018). This means that even though Singapore's high economy secures the supply of good quality and affordable food for Singaporeans today, this food security is highly sensitive to natural resource scarcity and climate events such as flooding, droughts or temperature

rise. Singapore produces locally only around 10% of its food supply, and consequently relies highly on imports (SFA, 2019a). This causes a strong vulnerability to trade and supply chain disruptions, because exporter countries might decide to reduce their exports of food to Singapore in case they fear for their own food security, due to e.g. a natural event that affected their production.

To reduce that vulnerability, Singapore announced beginning of 2019 the implementation of several new audacious policies (Zulkifli, 2019). Among them is the “30-by-30” plan, whose goal is to have 30% of domestic consumption covered by domestic production by 2030 (Zulkifli, 2019). Through this decision, Singapore aims at increasing its self-sufficiency ratio (SSR), which can be quantified using the following formula from the FAO (2012) for fresh seafood (FS):

$$SSR_{FS} = \frac{\text{production FS}}{\text{total domestic demand FS}} = \frac{\text{production FS}}{\text{production FS} + \text{imports FS} - \text{exports FS}} \quad (\text{Eq.3})$$

The goal of the Singaporean government could therefore be defined as:

$$SSR_{FS} \geq 0.3 \quad (\text{Eq.4})$$

SSR for processed fish is complex to determine because it is challenging to know whether processed seafood was produced using domestic fish or imported fish. It is therefore not referred to in this study.

Capture fisheries are not expected to increase in the coming years in Singapore (SFA, 2019b). Therefore, all the increasing production of seafood is expected to originate from aquaculture. Important challenges to the development of aquaculture in Singapore include the limited land availability and high incomes. Indeed, with 720 km² and around 5.6 million inhabitants, Singapore is a highly populated island (SINGSTAT, 2019). Land has been historically used for accommodation in priority, hence the limited production of food, an activity which is often land-intensive. Therefore, it is likely that land-optimized aquaculture systems would be preferred, which usually is the case only for high-technological systems. Additionally, the high cost of life and its associated high labor cost in the city-state compared to its neighbors is a disadvantage for Singapore because it implies higher prices than if the same goods were produced in other Southeast Asian countries. To ensure competitiveness, it is therefore likely that Singapore decides to encourage investments in innovative and SOTA aquaculture technologies, which usually require less workforce and less land. Such development would contribute to the image of Singapore as a major seafood tech-hub and support the Singaporean Economic Development Board position stating that the country should aim at becoming the “Asian technology capital” (EDB, 2018; SFA, 2019b).

In that context, the framework developed in Chapter 4 was applied on Singapore and its “30-by-30” policy implemented on the aquaculture sector. The period 2017-2040 was assessed to have perspective beyond the policy’s target.

5.1.2 Step 1: Description of the aquaculture sector

In 2017, the Singaporean seafood industry had a rather modest annual production of 6387 tons/year, among which 84% originated from aquaculture and 16% from capture fisheries (FAOSTAT, 2019a, 2019b). From the approx. 130 seafood farms, about 115 produced marine fishes for an annual production of 4516 tons/year, and with a majority of high-value species such as barramundi, milkfish or pompano (FAOSTAT, 2019a; SFA, 2019b).

Building upon national statistics and communications with local farmers and the Singapore Food Agency (SFA), the Singapore seafood sector was disaggregated into four species groups: marine fishes, freshwater fishes, crustaceans and mollusks. This grouping was based on the intrinsic differences between species that involve the use of different technologies to fish/farm them. Furthermore, two types of aquaculture technology were identified as currently used for marine fishes, and one for each of the other species groups. These technology types were gathered as “low-tech” or “high-tech”, based on the difference in terms of inputs required during the farming phase, and on the level of knowledge required from the farmer to operate the production system. An analysis of the literature on Asian aquaculture and personal communication with the SFA allowed identifying two SOTA technology types that are likely to be used in the future in Singapore: RAS and offshore systems. Combining the four technology types and the four species groups formed 8 production categories for the Singaporean aquaculture, which are displayed and described in Table 2. Some technologies involve that fingerlings cannot be put directly in the grow-out environment due to high mortality rates below a certain size/weight (e.g. if in the open sea), and therefore an extra step of juvenile growth is needed which usually occurs in the same facilities than the grow-out step. Both juvenile and grow-out technologies are described in Table 2.

Singapore's small capture industry mainly produces marine fishes and crustaceans. Adding its modest production of processed seafood, the domestic seafood supply in Singapore comports 11 categories:

- Marine fishes in “low-tech” systems (MF-LT)
- Marine fishes in “high-tech” systems (MF-HT)
- Marine fishes from capture (MF-CAP)
- Marine fishes in RAS (MF-RAS)²
- Marine fishes in offshore systems (MF-OFF)²

² Future technologies, not present in Singapore yet (or at pilot level)

- Freshwater fishes in “low-tech” systems (FF-LT)
- Freshwater fishes in RAS (FF-RAS)²
- Crustaceans in “high-tech” systems (CR-HT)
- Crustaceans from capture (MF-CAP)
- Mollusks in “low-tech” systems (MO-LT)
- Processed seafood (Proc)

Table 2: 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 a “*” symbol. Excerpt from Paper V.

Species group	Technology type	Category abbreviation	Juveniles growth	Grow-out system	Feed	Open /closed
<i>Marine fishes</i>	“Low-tech”	MF-LT	Fiberglass tanks equipped with a 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 a 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
<i>Freshwater fishes</i>	“Low-tech”	FF-LT	Fiberglass tanks equipped with a flow-through water system.	Concrete ponds dig in the ground with a flow-through water system.	Industry by-products	Closed
	RAS*	FF-RAS*	Fiberglass tanks equipped with a highly optimized water recirculating system.		Dry pellets	Closed
<i>Mollusks</i>	“Low-tech”	MO-LT	Long lines and plastic barrels attached to floating platforms made of wood and plastic.		Unfed	Open
<i>Crustaceans</i>	“High-tech”	CR-HT	Individual plastic boxes equipped with a highly optimized water recirculating system.		Fresh seafood	Closed

5.1.3 Step O: Micro-scale LCA

This section is based on elements from **Paper IV**; all results are therefore sourced from that paper, which for readability reasons, is not referenced systematically.

No LCA study has ever been conducted on Singaporean aquaculture before and little amount of LCA studies were conducted on Asian aquaculture in general (see section 3.2.1). Thus, an additional LCA study at micro-level was conducted as described in the

optional step O of the framework to get an overview of the environmental performance of the different production categories identified in step 1.

Goal and scope definition

The goal of the micro-scale LCA study was to (i) compare the environmental impacts of the 8 aquaculture production categories identified in Singapore in step 1 for the years 2017 and 2040, and (ii) identify environmental hotspots along their life cycle to highlight potential improvement sources. The 8 production categories assessed are described in Table 2 (section 5.1.2).

The literature review highlighted the dominance of feed production in a majority of past LCA studies on aquaculture. It is thus likely that feed production and use will undergo important changes in the future. As discussed in section 3.1.2, several options seem promising from an environmental perspective. The pressure on wild stocks due to the use of fresh fish from capture fisheries has often been qualified as a major issue linked to aquaculture production (Naylor et al., 2009). Therefore, two options to reduce the use of marine resources were investigated in this study. The literature review revealed two main strategies possible for that purpose: reducing the impacts of FMFO production and replacing FMFO with other ingredients. Therefore, the two Feed options compared for the year 2040 are (1) increasing the part of trimmings in the production of FMFO, and (2) replacing FMFO by insect-based meal and algal oil. Replacing fresh fish by trimmings in FMFO manufacturing is already a trend within feed producers because it reduces the costs of feed as well as the environmental impacts, and several leader aquafeed companies stated their willingness to increase this proportion for environmental purposes in their annual sustainability reports (as e.g. EWOS, 2015 and Cargill, 2017). The specific ingredients tested in Feed option 2 were selected due to their nutritional characteristics that theoretically allow them to replace FMFO in most fishes diets (Burr et al., 2012; Shah et al., 2017).

The FU was defined as “the yearly-averaged production of 1 ton of edible seafood for Singaporean households for the years 2017 and 2040”. The system boundary was as described in Figure 10, and the following elements were excluded from the study: harvesting (boats and fuel), cages/nets cleaning, boats manufacturing and materials, generators manufacturing and materials, use of medicine, drugs and vaccines, infrastructures/consumables transport to the farms, transport of the final product to retailer and to consumer, retailing and cooking. When juveniles and grow-out steps were separated, inputs and outputs linked to feed, infrastructures/equipment, consumables and farming stages of these two steps were gathered. Only marine fishes produced in offshore and “high-tech” systems needed post-farming processing due to the size of the fishes (4.5 kg), but the impacts of all categories at farm gate were divided by an edible fraction to obtain the impacts per mass of edible seafood. These edible factors varied depending on the species. Multifunctionality was handled following the ISO standards

recommendations. The processing of most food ingredients involved one or several co-products, which usually fulfilled the function of animal feed and were commonly used for that purpose. Therefore, as it constituted a conventional way to provide this function, allocation based on gross energy was used to solve this multifunctionality. Co-products of the manufacturing of algal oil were not considered as conventional, and therefore system expansion was used. By-products from the feed or food industry were considered as waste and were therefore associated with no impacts. The use of the sludge formed by uneaten feed and feces as natural fertilizer was modeled using system expansion through an avoided production of synthetic fertilizer. The modeling was attributional.

Life cycle inventories construction

To build the LCIs, primary data were collected in 13 major Singaporean farms using the questionnaire displayed in Appendix 1. The questions addressed all elements of the farming stage, including feed composition and origin, FCR, equipment, infrastructures, use and origin of energy/water/consumables (e.g. cleaning products, oxygen)/fingerlings, and farming techniques. All species groups and technology types were covered by the data collection. The farms visited were mostly large producers that had contact details available on the internet (e.g. on a company website). Smaller farms were harder to include in the study for two main reasons. The first one was that they were harder to contact in the first place because they do not usually have a website or other types of marketing material that would make their contact details available to the public. Therefore, the only way to create contact with them was to show up at their farms unattended, which implied to know the farm's address and was often perceived as intrusive by the farmers, who were then less inclined to collaborate. Another way was to obtain their contact from official organizations such as the SFA, but including the regulating entity could be perceived as threatening by the farmers who were afraid that if they were performing badly in the environmental study it could be a source of trouble with the SFA. The second reason was that in general, small farms' owners did not see any benefits in participating in the study and saw it as a loss of time because they did not intend to optimize their systems technologically, whereas larger companies were interested in having their systems assessed in case opportunities of improvements/optimizations would emerge from the assessment.

Since the data collected did not cover the full Singaporean industry, it was analyzed carefully to determine which farms or flows should be qualified as outliers and should therefore be disregarded. Approximately 10 farms were kept for the LCI construction after that step. For confidentiality reasons, the exact amount of farms used for each category as well as their names and species produced cannot be shared. Once this was done, country-representative inventories were formed for each production category based on the remaining farms and flows averaged over the annual production of each farm, as described in section 4.3.2. Future technologies were modeled based on literature and adapted to the Singaporean context.

The consequential version of the ecoinvent v3.5 database was used despite the attributional modeling to favor the use of system expansion in the background system, and because the resulted use of the marginal technology mix was considered negligible for most processes of the current study except electricity. The electricity production processes were therefore adapted to use the average mix of 2017 and 2040, for the countries of the foreground system, i.e. Singapore, Malaysia (production of fingerlings), Vietnam (production of marine-based ingredients and feed pellets) and China (production of plant-based ingredients). Some processes were adapted from the Agri-footprint v4.0 with ecoinvent inputs/outputs for homogeneity (Durlinger et al., 2017; Wernet et al., 2016). The software Simapro v9.0.0.49 was used to construct the model and to assess it (PRé Consultants, 2018).

These inventories were generated for the reference year 2017. Adapting them to the year 2040 required to apply changes to the following parameters and processes: the feed production, the FCR, the water and energy use during the farming phase and the electricity grid mix. Table 3 summarizes and describes the selected parameters/processes with the corresponding changes.

Table 3: Changes in the life cycle inventories of Singapore between 2017 and 2040. Adapted from Paper IV.

Change type	Parameter/process impacted	Change between 2017 and 2040
Feed ingredients	<i>Feed option 1</i> Fishmeal and fish oil production	Part of FMFO produced from by-products increases from 44% in 2017 to 80% in 2040.
	<i>Feed option 2</i> 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.
Farming optimization	Water need	Decrease by 10 to 20% depending on technology maturity ¹ .
	Energy need	Decrease by 10 to 20% depending on technology maturity ¹ .
	Feed conversion ratio	Decrease following historical trends of the period 2000-2015.
Electricity grid mix	Electricity production source and percentages	According to Asia Pacific Energy Research Centre (2016).

¹ Determined based on communication with the SFA and my own expert opinion.

More details about the inventories building as well as all sources and assumptions are available in **Paper IV**. The complete LCIs are disclosed transparently in **Supplementary Information B** of **Paper IV**.

Life cycle impact assessment

The impact categories included in the study are listed in Table 4 and were chosen to cover a large variety of impacts as recommended in the literature review (section 3.3.4). Methods found common in the literature review (see **Papers IIa,b** and Chapter 3) were prioritized, such as CML for acidification, eutrophication and land use, to allow comparability of the results with past studies. Based on the recommendations of the literature review (section 3.4), the NPPU was also assessed, using the method developed by Papatryphon *et al.* (2004). For marine ingredients, the formula from Pauly and Christensen (1995) was applied, which is:

$$\text{NPPU} = (M/9) * 10^{T-1} \text{ (Eq.4)}$$

where M is the wet mass of the organism and T is its trophic level. The average trophic level of fish inputs was determined using the global mixes of fish species used for FMFO production, which was assumed representative for FMFO produced in Vietnam (hypothesized origin of the FMFO used in Singapore - SEAFISH, 2018). For land-based ingredients, the crop carbon content was used (Papatryphon *et al.*, 2004). A definition of all impact categories included in this study is available in the Glossary (at the end of the manuscript).

Table 4: Impact categories included in this study, with their associated unit and method. Adapted from Paper IV.

Impact category	Unit	Method / References
Climate change short term	kg CO ₂ equivalent	IPCC GWP100a (Bulle <i>et al.</i> , 2019)
Eutrophication	kg PO ₄ ³⁻ equivalent	CML-IA v3.05 (Guinée <i>et al.</i> , 2001)
Acidification	kg SO ₂ equivalent	CML-IA v3.05 (Guinée <i>et al.</i> , 2001)
Land competition	m ² a	CML-IA v3.05 (Guinée <i>et al.</i> , 2001)
Fossil and nuclear energy use	kg depleted	IMPACT World+ v1.26 (Bulle <i>et al.</i> , 2019), same than the cumulative energy demand by Frischknecht <i>et al.</i> (2007)
Freshwater ecotoxicity	CTUe	USEtox v2.0 (Rosenbaum <i>et al.</i> , 2008)
Human toxicity cancer	CTUh	USEtox v2.0 (Rosenbaum <i>et al.</i> , 2008)
Human toxicity non cancer	CTUh	USEtox v2.0 (Rosenbaum <i>et al.</i> , 2008)
Mineral resource use	kg depleted	IMPACT World+ v1.26 (Bulle <i>et al.</i> , 2019)
Water scarcity	world m ³ equivalent	Available WATER Remaining (Boulay <i>et al.</i> , 2018)
Net primary production use	kg C	Method by Papatryphon <i>et al.</i> (2004)

Description of the life cycle inventories per production category

The main flows of the farming phase of the 8 production categories are presented in Table 5. The analysis of these flows revealed that the FCR of “low-tech” categories is in general around twice higher than the one of “high-tech” categories, which is itself slightly higher than the one of SOTA technologies. Regarding energy consumption, systems having their grow-out phase onshore, i.e. freshwater fishes in “low-tech” systems, crustaceans in “high-tech” systems and fishes in RAS, usually use electricity from the grid. The other systems have their grow-out phase at sea, and therefore use generators powered with fuel. Additionally, these systems have fuel needs to power their boats used to reach platforms/cages at sea. It can be seen in Table 5 that offshore systems have 4 times higher fuel consumption for boats than “high-tech” systems, corresponding to the fact that they are on average 4 times further from the shore. Another important difference between these two types of systems resides in nutrient management. Production systems that have their grow-out phase on land are all closed systems in this study, and the sludge formed by the uneaten feed and feces is modeled as sold to local agriculture farmers as natural fertilizer and therefore avoid the production of synthetic fertilizer. All the other systems of this study, i.e. systems that have their grow-out phase in the sea, are open systems and the above-mentioned nutrients are emitted in water where it can cause damages due to the eutrophying properties of these nutrients. Land occupation during grow-out is found especially high for crustaceans due to the use of individual boxes, despite their vertical layout. Freshwater fishes in “low-tech” have the second higher need for land during the farming phase, far ahead of the other systems. Water consumption is null for “low-tech” systems because these systems were found to usually use rainwater instead of freshwater.

Table 5: Energy, land and water inputs, emissions to water, avoided products and FCR of the 8 technologies and species for the farming stage, based on the production of 1 ton of edible seafood (CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system). Adapted from Paper IV.

	MF-LT	MF-HT	FF-LT	CR-HT	MO-LT	MF-OF	MF-RAS	FF-RAS
FCR in 2017	4.42	1.70	4.00	2.20	n.a.	1.70	1.50	1.50
FCR in 2040	3.96	1.46	4.00	1.69		1.22	1.02	1.02
<i>Inputs at farming stage (2017)</i>								
Electricity (kWh)	-	-	155	23191	-	-	10920	13650
Fuel - generator (kg)	499	676	-	-	6.77	676	1.66	2.08
Fuel - boats (kg)	81	203	-	-	13	889	-	-
Water (m ³)	0*	27.4	0*	30.3	0.2	27.4	23.4	29.2
Land occupation (m ² a)	7	20	325	1250	21	20	27	33

Sea occupation (m ² a)	241	39	-	-	694	20	-	-
<i>Emissions to water</i>								
Phosphorus (kg)	126	38	-	-	-0.7	39	-	-
Nitrogen (kg)	458	164	-	-	-9	174	-	-
Carbon (kg)	-	-	-	-	-182	-	-	-
<i>Avoided products</i>								
Fertilizer as P (kg)	-	-	71	10	-	-	30	38
Fertilizer as N (kg)	-	-	234	383	-	-	88	110

The detailed feed composition used by each production category in this study is presented in Table 6. Marine fishes in “low-tech” and “high-tech” systems use feed pellets with similar content of fishmeal but different content of fish oil. “Low-tech” farms usually seek to reduce prices in any way possible, and the relatively expensive price of fish oil might explain why these farms barely use this ingredient. Another explanation is that the fish species reared in these systems are slightly different than in “high-tech” systems today, as they are usually lower value ones, which might have metabolically lower needs for fish oil. Freshwater fishes in “low-tech” systems are modeled in this study as fed exclusively with industry leftovers, which is another way to reduce the costs of feed.

Table 6: Composition of the different feed used in 2017 and 2040 (CR=Crustaceans; FF=Freshwater fishes; MF=Marine fishes). Excerpt from Paper IV.

Ingredients	MF ₁	MF ₂	MF _{future}	FF ₁	FF ₂	FF _{future}	CR
<i>Used in...</i>	<i>MF-LT</i>	<i>MF-HT; MF-RAS; MF-OF</i>	<i>MF-HT; MF-RAS; MF-OF</i>	<i>FF-LT</i>	<i>FF-RAS</i>	<i>FF-RAS</i>	<i>CR-HT</i>
Fishmeal	0.45	0.44	0.22	-	0.10	-	-
Fish oil	0.01	0.16	0.08	-	-	-	-
Soybean meal	0.10	0.29	0.35	-	0.44	0.44	-
Maize starch	0.04	0.11	0.11	-	0.14	0.14	-
Rice bran	0.03	-	-	-	-	-	-
Wheat bran	0.04	-	-	-	-	-	-
Wheat flour	0.08	-	-	-	-	-	-
Wheat middling	-	-	-	-	0.30	0.30	-
Rape oil	-	-	-	-	0.02	0.02	-
Fresh fish	0.13	-	-	-	-	-	0.70
Industry leftovers	0.13	-	-	1.00	-	-	0.30
Insect based meal	-	-	0.16	-	-	0.10	-
Algal oil	-	-	0.08	-	-	-	-

Comparative assessment of the production categories in 2017

Figure 13 shows the ranking of the different production systems assessed for the 11 impacts categories, as well as their average rank for 2017 and 2040 with both Feed options. Figure 14 presents the results of the micro-scale LCA study, and displays the impacts per ton of edible seafood produced for the 11 impact categories differentiated by life cycle stages as in the system boundary of Figure 10. In general, marine fishes in “low-tech” systems, freshwater fishes in RAS and crustaceans in “high-tech” systems have the highest environmental impacts per ton of seafood produced in 2017. Contrarily, freshwater fishes and mollusks in “low-tech” systems perform the best, mainly due to their very low needs in terms of feed and energy. The first one even has negative scores for 8 impact categories due to the use of its nutrient sludge as natural fertilizer, which creates an offset from the avoided production of synthetic fertilizer due to the use of system expansion.

	Acidification	Climate change, short term	Eutrophication	Freshwater ecotoxicity	Human toxicity cancer	Human toxicity non cancer	Land competition	Mineral resources use	Net primary production	Water scarcity	Fossil and nuclear energy use	Average 2017	Average 2040 Feed option 1	Average 2040 Feed option 2
CR-HT												5.5	6.1	5.5
FF-LT												1.0	1.0	1.0
FF-RAS												6.5	6.5	5.6
MF-LT												6.2	6.3	5.2
MF-HT												4.2	4.4	5.7
MF-RAS												4.5	4.5	4.9
MF-OF												6.0	5.2	6.0
MO-LT												2.0	2.0	1.9

Figure 13: Ranking of the 8 technologies for the 11 assessed environmental impact indicators. Green cells indicate systems with lowest impacts and red those with highest impacts. The averaged rank over these 11 environmental impact indicators in 2017 and 2040 for Feed options 1 and 2 is shown in the last three columns. Excerpt from Paper IV.

Production of marine fishes seems to have a larger variability with other species groups than between technologies. Yet, “high-tech” systems are generally the best option as it ranks lowest or second lowest for all environmental impacts. Production of marine fishes in “low-tech” systems has generally, as stated already above, high impacts, except for freshwater ecotoxicity and human toxicity cancer for which it has the lowest impacts among marine fishes thanks to its low energy consumption. On the other hand, RAS has the lowest impacts on human toxicity non-cancer, land competition, mineral resource use and eutrophication among the marine fishes technologies. Therefore, it seems that there is a risk of burden-shifting if switching from current to future technologies for this species group, because the implementation of new technologies would most likely reduce

impacts on eutrophication and NPPU while increasing toxicity impacts. In the sensitivity analysis, the results of the RAS is found to be highly dependent on the electricity consumption, so if the environmental impacts of the electricity production decrease or if the RAS reduces its consumption, this trade-off might be limited.

With these potential environmental trade-offs, it is difficult to conclude on which technology should be preferred, but the “high-tech” and the RAS systems seem to have the most benefits in 2017.

Hotspot analysis in 2017

It can be observed in Figure 14 that impacts are generally dominated by the feed production. However, this dominance decreases when the optimization/innovativeness of technology increases. Indeed, the more optimized a technology is, the better the feed management is, leading to lower FCR and therefore less feed use, but this usually happens at the cost of higher energy use. In the sensitivity analysis, the FCR is found to have a large influence on the results of all production systems.

Figure 14: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2017 for the 8 production systems under study. Graphs show differentiation between life cycle stages. Excerpt from Paper IV.

Feed is the only contribution to NPPU impacts; hence, NPPU scores present only feed and post-farming (when applicable) distribution. NPPU scores from post-farming stages are always negative because it is linked to the use of trimmings from gutting and filleting in the production of e.g. FMFO, which leads to an avoiding production of fresh fish due to the use of system expansion.

Figure 15: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2040 for the 8 production systems under study. Graphs show differentiation between life cycle stages. Except from Paper IV.

Comparative assessment of the production categories in 2040

As it can be observed from Figure 13, few changes occur in the ranking of the different categories between 2017 and 2040. With Feed option 1 (i.e. increasing part of trimmings

in FMFO manufacturing), the only difference is that crustaceans in “high-tech” systems and marine fishes in offshore systems switch rank, the former becoming worse. With Feed option 2 (i.e. replacing FMFO by insect-based meal and algal oil), more noticeable changes occur and marine fishes in “high-tech” and offshore systems become the options with the highest environmental impacts in general, closely in front of marine fishes in “low-tech” systems and crustaceans. Contrarily, the two RAS systems perform better because of their lower FCR. In general, impacts decrease with Feed option 1 and increase with Feed option 2 between 2017 and 2040.

Details about the evolution of each of the 8 production systems in 2017 and 2040 are available in **Paper IV**, as well as the detailed results of the sensitivity analysis.

Putting the results in perspective: past studies and development potential

The results obtained in the micro-scale LCA can be compared with the retrieved results from past studies for several impact categories. They are found consistent and usually corresponded to the lower side of the range formed by past studies. Despite the non-alignment of methodological choices within the studies reviewed (e.g. regarding the handling of multifunctionality), the results and background data of the current study can overall be validated. However, to put the results of the impact assessment of the micro-scale study in perspective, it is necessary to determine which production categories have a real potential to increase their production in Singapore.

Even though freshwater fishes produced in “low-tech” systems are associated with the lowest environmental impacts in all impact categories assessed in the study, increasing the number of farms of this category appears as very difficult. The first issue regards the need of land during grow-out, which is 325 m²a per ton of edible fish produced (see Table 5). This is approximately 10 times higher than the other systems assessed here (except crustaceans in boxes), but this is not reflected in the land use impact category because this impact category is largely dominated by feed production and not grow-out, and that the LCIA method used does not consider land scarcity (i.e. 1 m² of land has the same impact wherever it is situated). However, for Singapore, land is a very scarce resource, as already discussed before. Land use in the city-state itself is therefore of great importance in the decision process and land-intensive technologies are unlikely to be encouraged by the government.

The second issue is that the low impacts of this production category rely exclusively on the combination of two assumptions: the feed is composed of industry by-products and the produced nutrient sludge is reused as natural fertilizer. The possibility of doing both of these would be challenged if the production increase, due to the limited agriculture production and animal husbandry in Singapore. There are only that much chicken leftovers available in Singapore and there is only that many farms willing to use natural fertilizer to replace synthetic one. Moreover, it is found in the sensitivity analysis that if chicken leftovers were not considered as waste but as co-products, this production

category would lose its environmental benefits and become among the worst option of the study. The production of crustaceans in “high-tech” systems faces similar limitations, as its land requirements are the highest of the study (1000 m²a according to Table 5) and most of its (already lukewarm) environmental benefits rely on the use of its nutrient sludge as natural fertilizer.

Mollusks in “low-tech” systems have as well important limitations that would prevent the intensive development of this culture type in Singapore. Mollusks are unfed organisms, meaning that they feed on nutrients present in their surrounding environment; therefore, their ability to grow relies heavily on the water quality. On top of that, mollusks are especially vulnerable to predators and invasive species.

On the other hand, marine fishes in “high-tech” and offshore systems have a high potential of increasing their production in Singapore. The land is not an issue as the grow-out stage occurs at sea, but the main risk is rising eutrophication in coastal areas due to nutrient emissions in water. This issue would be reduced if the farming happened further from the coast, as in offshore systems. However, this advantage is not visible in the current study because common eutrophication indicators do not include such spatial differentiation. This advantage unfortunately comes with longer boat trips to visit the cages and therefore an increase in energy use and climate change impacts, as witnessed in Figure 15. It is possible to reduce this trade-off by optimizing the number of trips to the cages (e.g. using automatic feeders, cameras or other detection systems) or by using less polluting boats. RAS is an especially tempting technology type for Singapore as well, as it can be built inside buildings, on rooftops or vertically to decrease land use. Its environmental performances for marine fishes are found to be among the lowest of this study in 2040 with Feed option 1, and could be decreased even more if the environmental impacts of electricity production were to decrease in Singapore (e.g. if the part of fossil fuel decreased) or if farms were to install photovoltaic panels to avoid consuming electricity from the grid. These advantages could be found for freshwater fishes in RAS as well if the aquafeed had lower environmental impacts (see Figure 14).

Therefore, marine fishes in “high-tech”, offshore systems and RAS appear to have the most benefits for Singaporean aquaculture thanks to their relatively low environmental impacts and low land requirements. Despite these interesting conclusions, this LCA study does not address thoroughly the implications of the “30-by-30” policy, as it e.g. only considers two years of the time-scope, does not account for gradual penetration of the new technologies and does not include any economic considerations. To assess comprehensively the implications of new aquaculture growth policies, construction of scenarios for aquaculture development and their assessment via a macro-level LCA study is still necessary.

5.1.4 Step 2: Scenarios construction

This section is based on elements from **Paper III**; all results are therefore sourced from that paper, which for readability reasons, is not referenced systematically.

Step 2.1: Identifying the target

The target of the “30-by-30” policy is straightforward to identify, and can be expressed as “increasing the self-sufficiency factor of fresh seafood (SSF_{FS}) to 0.3 or more by 2030” as detailed in section 5.1.1 (Eq.4).

Step 2.2: Defining scenarios

The three developed scenarios are described below:

- *Business-as-usual scenario (SG-BAU)*: No important measure is taken to implement the policy. Production via innovative technologies (RAS, offshore and “high-tech”) increases moderately by 5% yearly, while the supply of other production systems stays constant.
- *Scenario 1 (SG-S1)*: Singapore decision-makers implement strategic incentives for all aquaculture production technologies. Consequently, innovative technologies have an important annual increase until 2030 and “low-tech” has a moderate increase before the same year.
- *Scenario 2 (SG-S2)*: Singapore decision-makers implement strategic incentives focusing on production from innovative aquaculture technologies to turn Singapore into a tech-hub. Innovative technologies increase more than in SG-S1 while the production in “low-tech” ones remains constant.

In both SG-S1 and SG-S2, SSF_{FS} is strengthened and is expected to reach 0.3 around 2030. All chosen technological factors are available in **Paper III**.

Step 2.3: Adapting the Asiafish model

As explained in section 4.4, the technology used to produce a food item does not influence consumers’ purchasing decisions, and therefore only 5 demand categories are needed in the Singapore case study to correspond to the 11 supply categories defined in section 5.1.2. This is illustrated in Figure 16.

Figure 16: Structure of the AsiaFish model adapted for Singapore, with the different supply, demand and matching categories, i.e. trade. Excerpt from Paper III.

Data from the FAO were used to populate the model in terms of seafood production and trade (FAOSTAT, 2019a, 2019b, 2019c) while the source of most economic and demographic inputs was the Singaporean Department of Statistics (SINGSTAT, 2019). Table 7 presents the seafood demand-supply balance in Singapore, for the 11 supply categories and the 5 demand ones. The reader is invited to refer to **Paper III** for details about how it was built.

Table 7: Seafood balance for Singapore in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories. Excerpt from Paper III.

	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
	Capture	Low tech	High tech	RAS	Offshore	Low tech	RAS	Low tech	Capture	Low tech	
<i>Production</i>	746	4,516	105	0	0	291	0	353	269	212	44,352
	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
<i>Consumption</i>	8,488					4,912		3,540	13,162		137,843
<i>Export</i>	1,196					191		16	42		14,922
<i>Import</i>	38,376					4,812		4,720	13,416		108,413
<i>Intermediate</i>	33,953					0		1,517	693		n.a.

Table 8: Seafood balance for Singapore in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories. Excerpt from Paper III.

	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
	Capture	Low tech	High tech	RAS	Offshore	Low tech	RAS	Low tech	Capture	Low tech	
<i>Production</i>	3,656	21,608	515	0	0	2,931	0	289	5,762	4,537	221,607
	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
<i>Consumption</i>	29,786					24,556		10,982	97,483		693,719
<i>Export</i>	5,927					588		272	676		88,439
<i>Import</i>	129,070					22,213		15,672	92,990		560,551
<i>Intermediate</i>	119,142					0		4,707	5,131		n.a.

A review of the literature revealed that no expenditure, demand or supply elasticities were available for species groups differentiated as in this study. Therefore, generic elasticities for Singapore were used for all species groups. No data was found either on cross-price elasticities of demand, but since non-substitutability and non-complementarity were assumed across groups, all cross-price elasticities were set to zero. Perfect substitution was assumed within each group and therefore supply elasticities were all set to zero. A comprehensive list of the model's sources and assumptions is available in **Paper III**.

Using elasticities developed specifically for this study, i.e. with adapted differentiation and time-scope, would have increased the quality of the results produced. Yet, economic studies that retrieve elasticities are very resource intensive and require deep knowledge of specific economic fields. It was therefore not possible to conduct such study for the sake of this project. However, if the adapted elasticities were to be produced in the future and become available, it would be valuable to include them in the model, re-do the study and compare the obtained results.

Step 2.4: Generating scenarios

The scenarios described in section step 2.2 were generated using the Asiafish model. The results obtained are available in **Supplementary Information of Paper III** and discussed in the following paragraph.

Step 2.5: Analyzing the scenarios

A consistency check was conducted on the results obtained, and it was concluded that the results were consistent with the expected outcomes. The variations of quantities produced, imports, exports and consumption corresponded to the implemented changes,

and the prices variation within the time-scope was considered reasonable enough to be realistic. A detailed analysis of the prices obtained is available in **Paper III**.

Figure 17: Total domestic production, consumption and imports of fresh fish and processed fish in Singapore for the three scenarios during the period 2017-2040; the difference between the total domestic demand and the cumulated stacked curves equals the exports. Excerpt from Paper III.

Figure 17 gives an overview of the total Singaporean domestic supply, demand and imports in terms of seafood during the period 2017-2040. Domestic production increases in all three scenarios, even though the increase is much bigger for SG-S1/S2 (multiplied by 5.8 and 9.4 respectively, whereas it increases by only 10% in SG-BAU). Even though seafood consumption per capita remains stable over the whole period, total domestic consumption increases in all scenarios due to an increase of population (yearly increase of 1.33% from 2017 to 2030). Consequently, seafood imports increase in SG-BAU between 2017 and 2040 because the increase in production does not cover entirely the increase in demand, but it decreases in SG-S1/S2 by 9%/28% thanks to the increase in production. Thereby, SSF_{SF} increases from 0.1 (2017) to 0.33/0.34 (2030) and finally reaches 0.44/0.69 (2040) in SG-S1/S2.

The domestic production mix of Singapore can be observed in Figure 18b. In SG-BAU, marine fishes produced in “low-tech” systems remain dominant in the Singaporean aquaculture landscape through the whole period, and little variation in the production mix is observed. Contrastingly, the explorative scenarios present more diverse production

profiles. SG-S2 is dominated by SOTA technologies. Overall, the proportion of innovative technologies reaches 14% in SG-BAU, 73% in SG-S1 and 90% in SG-S2.

Figure 18: Domestic production (a) and annual distribution (b) for each of the species and technologies and the 3 scenarios in Singapore, and the years 2017, 2030 and 2040. Excerpt from Paper III.

In the light of these observations, it appears that the business-as-usual scenario does not allow Singapore to reach its goal in terms of seafood self-sufficiency, which confirms the needs of political actions to develop Singapore aquaculture consistently. On the other hand, both SG-S1 and SG-S2 fulfill the main goal of the policy, as SSF_{SF} reaches 0.3 in 2030, and innovative technologies become majoritarian in the production mix around 2020. However, these two scenarios are not equivalent. By implementing this policy, one of the main objectives of the Singaporean government is to reduce its dependence on imports. In scenario SG-S1, despite an important increase in production, imports undergo a maximum decrease of 9% compared to the quantities imported in 2017, due to the combination of increasing consumption but also exports, as export prices are

higher than domestic prices which encourage farmers to sell abroad instead of restraining themselves to the domestic market. Scenario SG-S2 presents a decrease in imports by 28% between 2017 and 2040, which might be considered enough by the Singaporean government. Therefore, combined with the fact that this scenario has a higher proportion of innovative technologies in its production mix through the assessed period, SG-S2 appears as the best solution for Singapore to fulfill its policy's objectives, in the context of its current socioeconomic and environmental constraints.

A sensitivity analysis was conducted, available in **Paper III**. The AIDS parameters, the CES/CET and the demand and expenditure elasticities were selected as the most uncertain parameters of the study. By making them vary by $\pm 10\%$, it was found that the model is moderately to highly sensitive to the AIDS parameters, but all other parameters tested were found to have a low sensitivity on the results.

5.1.5 Step 3: LCA methodology application

Goal and scope definition

The goal of the macro-scale LCA on Singapore aquaculture was to compare the evolution of the normalized environmental impacts of the construction of the different scenarios in step 2 through the period 2017-2040. The same two Feed options than in the micro-scale assessment were compared (for the same reasons), which are (1) increasing the part of trimmings in the production of FMFO and (2) replacing FMFO by insect-based meal and algal oil.

For this study, the FU was defined as “the average production (over a year) of 1 ton of edible seafood in Singapore in the period 2017-2040”. The system boundary and the way to handle multifunctionality were similar to the micro-scale study. The reader is therefore referred to section 5.1.3 for details about these two methodological aspects. As recommended in section 4.5.1, consequential modeling was used. The software Simapro v9.0.0.49 was used to construct the model and to assess it (PRé Consultants, 2018).

Life cycle inventories

Data collection and LCIs construction were similar to the micro-scale study and are described in section 5.1.3. The background system was also modeled using the ecoinvent v3.5 consequential database due to the consequential nature of the study. However, the average electricity mix was used instead of the long-term marginal one (as normally recommended in consequential studies by the ILCD handbook - EC, 2010), because it was assumed that the increase in aquaculture production in Singapore had a negligible influence on the total electricity demand in the countries part of the foreground system (i.e. Singapore, Malaysia, Vietnam, China). Furthermore, the variation of Singapore electricity mix is expected to be small between 2017 and 2040; therefore, the marginal and the average mixes are very similar. The electricity mixes of Singapore, Malaysia, China

and Vietnam were time-differentiated and varied yearly according to the predictions from Asia Pacific Energy Research Centre (2016). Finally, no changes in the aquaculture or food production of other countries were modeled because global food needs are constantly increasing, and the seafood that is not exported to Singapore would be exported to other countries that still have hunger issues. Therefore, the LCIs of the micro- and macro-scale studies were similar for 2017 and 2040.

To obtain the time-differentiation for years between 2017 and 2040, the changes as described in Table 3 were varied linearly through time.

Life cycle impact assessment

Based on the recommendations of the literature review (section 3.3.4), a comprehensive set of impact categories covering a large variety of environmental impacts was assessed. For that purpose, the newly developed impact assessment methodology IMPACT World+ was used with specially-differentiated characterization factors at Midpoint (v1.26 - 18 impact categories) and Endpoint (v1.43 - 2 AoPs) (Bulle et al., 2019). Additionally, the category NPPU, specially adapted for food production, was assessed based on the method developed by Papatryphon *et al.* (2004). Again, a description of all impact categories included in this study as well as the definitions of midpoint and endpoint are available in the Glossary (at the end of the manuscript).

Table 9: Impact categories assessed in this study with their corresponding unit and assessment level. For their description, see Glossary.

Impact category	Unit	Assessment level
Climate change, short term ¹	kg CO ₂ eq (short term)	Midpoint
Climate change, long term ¹	kg CO ₂ eq (long term)	
Land occupation, biodiversity ¹	m ² arable land	
Land transformation, biodiversity ¹	m ² arable land	
Fossil and nuclear energy use ¹	MJ deprived	
Mineral resources use ¹	kg deprived	
Water scarcity ¹	m ³ world-eq	
Freshwater acidification ¹	kg SO ₂ eq	
Terrestrial acidification ¹	kg SO ₂ eq	
Freshwater eutrophication ¹	kg PO ₄ P-lim eq	
Marine eutrophication ¹	kg N N-lim eq	
Freshwater ecotoxicity ¹	CTUe	
Particulate matter formation ¹	kg PM _{2.5} eq	
Photochemical oxidant formation ¹	kg NMVOC eq	
Human toxicity cancer ¹	CTUh	
Human toxicity non cancer ¹	CTUh	

Ionizing radiations ¹	Bq C-14 eq	Endpoint
Ozone Layer Depletion ¹	kg CFC-11 eq	
NPPU ²	kg C	
Human health ¹	DALY	
Ecosystems ¹	PDF.m ² .yr	

¹: From Bulle *et al.* (2019).

²: From Papatryphon *et al.* (2004).

5.1.6 Step 4: Results of the national-level assessment and interpretation

Figure 19 presents the results of the application of the framework to Singapore; it displays the evolution over 2017-2040 of the impacts per yearly-averaged ton of edible seafood produced in Singapore for the 3 developed scenarios and the 2 Feed options, hereafter referred to as the “normalized impacts”. In this section, the general trends of the different scenarios are investigated before an in-depth analysis of specific impact categories selected for their relevance in the context of aquaculture in Singapore is conducted.

General trends

It can be observed from Figure 19 that the impacts per yearly-averaged ton of edible seafood have limited variation in SG-BAU between 2017 and 2040 (max +/-20% - except for NPPU). In 2017, the aquaculture production mix in Singapore is dominated by marine fishes in “low-tech” systems, and the scenario SG-BAU remains largely dominated by this production category through the whole time-scope (discussed already in step 2.5 and illustrated in Figure 18). This technology, i.e. the use of nets in the sea attached to floating wooden-platforms, is soon-to-be obsolete and is therefore expected to gain little efficiency and to keep the same farming practices through the whole period, hence having little changes in its environmental impacts per ton of seafood produced between 2017 and 2040. This explains the little variation of the normalized impacts in scenario SG-BAU. Contrarily, Figure 19 shows that in SG-S1/S2, normalized impacts vary greatly between 2017 and 2040, and they are higher than SG-BAU for some impact categories and lower for others. This means that according to this study, selecting one of the two explorative scenarios over the business-as-usual one would lead to environmental trade-offs. This reflects the large introduction of innovative technologies in SG-S1 and SG-S2, as impacts that are usually associated to intensive systems, which is often the case for new technologies (e.g. toxicity impacts and energy-related impacts) are higher in these scenarios, while impacts that are historically burdens of traditional aquaculture due to its more extensive production (e.g. eutrophication and NPPU) are higher in SG-BAU (see section 3.2.3 and **Paper I**). Feed option 2 has in general higher normalized impacts than Feed option 1, due to the replacement of fishmeal by insect-based meal, an ingredient that is associated to higher impact scores in most impact categories.

Figure 19: Evolution between 2017 and 2040 of the characterized scores corresponding to 1 yearly average ton of edible seafood produced in Singapore in the 3 scenarios and the 2 different feed options, for the 18 impact categories of IMPACT World+ midpoint and NPPU (net primary production use) (A to S) and for the 2 areas of protection of IMPACT World+ endpoint (T and U). Excerpt from Paper V.

Endpoint level analysis reveals that normalized impacts of ecosystem quality increase for SG-S1/S2 while it remains relatively constant through the years for SG-BAU. This is explained by the dominance of “freshwater ecotoxicity long term” on this AoP combined with the increasing proportion of RAS in the explorative scenarios, which is the production category that has the highest scores per ton of edible seafood produced in this specific impact category (see step O and Figure 15). However, toxicity impacts in general are associated to high uncertainties because of, on the one hand, the large amount of substances that can potentially contribute to these categories but their limited coverage in current LCIA methods, and, on the other hand, the probable overestimation of characterization factors at endpoint (UNEP SETAC, 2019). Additionally, the long term version of this impact category is likely to be dominated by metals due to the models used that do not account for aging mechanisms of these substances after 3 years, which is likely to overestimate their contribution to long-term effects (UNEP SETAC, 2019). Feed option 1 is associated to lower normalized environmental impacts than Feed option 2 in this AoP due to the electricity need during algal oil production, which is associated with important freshwater ecotoxicity impacts. Regarding human health, normalized impacts of SG-S1/S2 increase with Feed option 2 and decrease with Feed option 1 over the period (Figure 19), due to the dominance of water availability and the high impact scores of insect-based meal in this impact category.

Focus on climate change

Normalized impacts of climate change have overall a limited variation during 2017-2040, remaining within the range of 11.3 to 13.7 tons CO₂-eq per ton of yearly-averaged edible seafood produced for all scenarios and all feed options. These numbers are consistent with the results from Henriksson *et al.* (2017), who found climate change impacts of Indonesian aquaculture in the range of 3-15 tons CO₂-eq per ton of live-weight seafood, which corresponds roughly to 6-30 tons CO₂-eq per ton of edible seafood (when applying the edible factor of marine fishes that is 0.5). Within this limited range, SG-BAU is associated with the lowest normalized impacts and SG-S2 with the highest ones during the whole period because of the increasing importance of marine fishes in offshore systems and freshwater fishes in RAS in this scenarios that are associated with slightly higher climate change impacts than marine fishes in “low-tech” systems (see step O and Figure 15). Higher normalized impacts accompany Feed option 2 for all scenarios due to the higher climate change impacts of insect-based meal compared to fishmeal.

Focus on eutrophication

The highest eutrophication impacts are associated to marine fishes produced in “low-tech” systems, and therefore the loss of importance of this technology in the production mix of SG-S1 and SG-S2 results in a radical decrease of the scores of this impact category (60 to 90% depending on the Feed option). Normalized impacts are approximately twice lower in SG-S2 than in SG-S1 due to the bigger penetration of RAS technologies in the

production mix of this scenario, which is a closed system, and therefore is associated with very low eutrophication impacts. Indeed, as evoked in section 3.2.3, open systems are associated with higher eutrophication impacts due to the emissions in open water of uneaten feed and feces (that contain phosphorus and nitrogen that are eutrophying substances) during their farming stage.

Focus on NPPU

As NPPU impacts are the highest for marine-based ingredients and the main goal of both Feed options is to reduce the use of marine resources, NPPU decreases from 2017 to 2040 in the 3 scenarios and for both feed options. However, the decrease is more important for Feed option 1 than Feed option 2, and is higher for SG-S2 than SG-S1 than SG-BAU. Normalized impacts are the highest in 2017 with 87 tons C per FU, and decreases down to 9.2 tons C per FU in SG-S2 with Feed option 1. In the literature review, an average NPPU per ton of live-weight seafood of 50 tons C was found, which corresponds roughly to 100 tons C per ton of edible seafood (see Figure 5 and **Paper I**). This suggests that Singaporean aquaculture has relatively low NPPU impacts, according to this study.

Focus on land impacts

Land is an especially scarce resource for the highly populated island of Singapore. Therefore, land-related impacts are of special importance in this case study.

Normalized impacts of land occupation decrease between 2017 and 2040 in the 2 explorative scenarios for Feed option 1, while they remain constant for Feed option 2. This is because the proportion of marine fishes produced in “low-tech” systems, a category associated with high land occupation, decreases in the production mix of these scenarios. When Feed option 2 is chosen, this decrease is compensated by the introduction of insect-based meal, whose production has higher land occupation than fishmeal (due to the use of plant-based ingredients to feed the insects during their production that is associated to important agricultural land requirements). However, the production of this ingredient is likely to occur outside Singapore (in the study it is assumed to take place in China). If looking solely at land occupation during the farming phase (i.e. in Singapore), both Feed options present similar contribution and the main difference relies then on the scenarios, with the advantage to SG-S2.

Normalized impacts of land transformation decrease for both explorative scenarios, with a small advantage for SG-S2 again, while it increases slightly in SG-BAU. This is mainly linked to the changing proportion of crustaceans in “high-tech” systems in the production mix of the different scenarios. This production category is associated to high land transformation impacts due to the important need of land during farming.

Uncertainties and limitations of the study

The study presented in this section presents a number of uncertainties. One of the most important uncertainties of this study is due to the input data of the prospective LCIs. These inventories are intrinsically uncertain due to the modeling assumptions and/or extrapolations involved. Additionally, as only a limited number of Singaporean farms have been visited, the LCIs corresponding to the production of aquaculture in Singapore are likely to be accurate but lack preciseness. Added to these are the uncertainties linked to the scenarios, which are also prospective. Most of these uncertainties could not be avoided due to the very nature of a prospective study. This is why several scenarios are built and different options are compared. The analysis of many options can be considered as a sensitivity analysis. It appears that choices regarding the feed are very important (which was also confirmed by the sensitivity analysis of the micro-scale LCA – step O). As the important variations between the different scenarios testify, the choice of technology and species influences greatly the LCA results.

5.1.7 Recommendations

Based on the results of the framework and their analysis above, recommendations for Singaporean decision-makers are produced. They concern which scenarios to get inspired from to reach the goal of their “30-by-30” policy with the lowest environmental impacts possible.

Overall, normalized impacts of SG-BAU present less extreme variations than SG-S1/S2 and this scenario offers slightly decreasing impacts per FU in most impact categories. It could therefore appear as an acceptable solution since while it does not generate an important decrease in impacts, it does not cause an important increase either. However, based on the analysis of the scenarios in section 5.1.4 (step 2.5), this scenario does not allow the Singaporean government to reach the objectives of the “30-by-30” policy, which means that the scenarios SG-S1 and SG-S2 are more likely to become true assuming that Singapore follows its new policy. These two scenarios have generally the same tendencies, though SG-S2 usually presents more extreme variations. This means that if normalized impacts are increasing (decreasing) in the explorative scenarios compared to SG-BAU, they are increasing (decreasing) more in SG-S2, strengthening the burden-shifting between increasing and decreasing impacts. However, a more thorough look at the numbers indicates that the difference between SG-S1 and SG-S2 is smaller than 7% in eco-efficiency over the whole period, except for two impact categories. This scenario is also assessed as the preferred solution from the economic analysis of the scenarios in section 5.1.4 due to a bigger decrease in imports and a higher proportion of innovative technologies. This suggests that overall SG-S2 is the preferred solution to get inspired of for the Singapore government to meet their policy goal while limiting the increase of environmental impacts in general.

This scenario implies a fast growth of the production from innovative technologies, and decision-makers may need to implement important incentives to allow Singapore to

develop that quickly. They could for instance implement financial aids for new farms using these technologies and for existing farms willing to transition to them. The number of Singaporean farms is likely to increase drastically, meaning that an important number of new companies will be created. By easing the creation process of new aquaculture companies of a specific type, Singapore government could boost their development. The strong emphasis on modern technologies could be used to attract foreign entrepreneurs willing to build SOTA aquaculture systems, as well as investors interested in high-tech companies.

Furthermore, the analysis of the results highlights that Feed option 1 is generally associated with lower environmental impacts than Feed option 2. Therefore, replacing fresh fish by trimmings in the production of FMFO seems to have higher environmental benefits than replacing this ingredient by insect-based meal and algal oil. As the production of FMFO is almost inexistent in Singapore, this information cannot directly be used by Singaporean authorities to influence the manufacturing of FMFO, but it could be used to encourage farmers to buy feed pellets that correspond to that description. For instance, special taxes could be introduced on FMFO that do not comply with a minimum amount of trimmings used in their manufacturing.

5.2 NORWAY – THE END OF THE SALMON’S REIGN?

5.2.1 Norway willingness to change its seafood production industry

Currently, Norway is a major actor of the global seafood production stage. It is the second biggest seafood exporter and the first producer of farmed salmon worldwide (FAO, 2016). The Norwegian government is determined to keep that leadership position in the industry with a continually growing yet sustainable production (Norwegian Ministries, 2019). Several challenges have contributed to stabilizing the Norwegian production of salmonids since 2012, which was a premiere after decades of growth (SSB, 2019a). Further development of the sector seems therefore to depend on how well and when these issues will be addressed (Lekang et al., 2016). Norwegian salmon farming is generally done in open systems with direct proximity to wild salmon populations, consisting of sea cages with a high density of specimens (Marine Harvest, 2016). The main concerns are disease control, in particular sea lice, and escapes of farmed specimen, and have consequences on both local ecosystems and productivity (Lekang et al., 2016).

The Norwegian government elaborated two complementary strategies to tackle the challenges of the current aquaculture industry and allow the growth of the aquaculture sector to continue (Norwegian Ministries, 2019; Norwegian Ministry of Fisheries and Coastal Affairs, 2009):

- Diversification in terms of technologies with the introduction of sustainable systems that would solve the identified problems.

- Diversification in terms of species through the introduction of non-salmonids farms to decrease the reliance of the entire sector on a single species.

Both are expected to reduce or suppress the pressures of the aquaculture industry on the Norwegian environment, and would contribute to make Norwegian aquaculture a pioneer in terms of sustainable seafood production (Norwegian Ministries, 2019). On the other hand, the Norwegian Ministries (2019) announced that capture should remain an important source of revenue but that more regulations will be implemented in order to maintain sustainable levels of fish stocks, which would lead to a stabilized level of production.

In that context, the framework developed in Chapter 4 was applied on Norway and used to compare the environmental impacts of the two above-mentioned approaches of the Norwegian government to diversify the aquaculture sector. The period 2017-2040 was selected to have a long-term perspective on the policy's consequences.

5.2.2 Step 1: Description of the aquaculture sector

With a production of 2.9 million tons of seafood in 2017, Norway is an important producer of both fisheries (55% of the production in mass) and aquaculture (45% of the production in mass) (SSB, 2019b). The capture sector covers a large variety of species, mainly marine ones due to Norway's geographical situation, and with an especially important production of pelagic fishes such as herrings and mackerels (SSB, 2019b). Contrarily, the aquaculture production consists of 95% of Atlantic salmon, for which the production techniques have been highly optimized through the years.

Based on national statistics, the Norwegian seafood sector was disaggregated into five species groups: salmonids, white fishes, oily fishes, crustaceans and mollusks. Each of these species groups is fished, but only one of them is intensively farmed today (i.e. salmonids). Furthermore, one type of technology was identified today for salmonids, i.e. sea cages. Some production of white fishes and mollusks have emerged recently, with the former being produced in sea cages as salmonids and the latter being usually produced in combination with salmonids in integrated multi-trophic aquaculture (IMTA) systems. Both of these are considered as future technology types with potential for development due to their very marginal presence in the production mix today. Two additional technology types were identified in an analysis of the literature for potential future production of salmonids: RAS and offshore systems. Combining the four technology types and the three species groups potentially farmed formed six production categories for the Norwegian aquaculture, which are illustrated and described in Table 10.

Table 10: 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. Excerpt from Paper V.

Species group	Technology type	Category abbreviation	Juveniles growth	Grow-out system	Feed	Open /closed
<i>Salmonids</i>	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 a 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
<i>Mollusks</i>	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
<i>White fishes</i>	Sea cages	WFSC	Fiberglass tanks equipped with a highly optimized water recirculating system (RAS).	Large cages in the sea built close from the shore, often in fjords.	Dry pellets	Open

Adding the five species groups being captured and the production of processed seafood, there are 12 categories of domestic seafood supply in Norway:

- Salmonids from sea cages
- Salmonids from capture
- Salmonids from RAS³
- Salmonids from offshore systems³
- Salmonids from IMTA³
- White fishes from sea cages³
- White fishes from capture
- Oily fishes from capture

³ Future technologies, not present in Norway yet (or at pilot plant level).

- Mollusks from IMTA³
- Mollusks from capture
- Crustaceans from capture
- Processed seafood

5.2.3 Step 2: Scenarios construction

Step 2.1: Identifying the target

The target of the assessed governmental strategies is to diversify the production of the aquaculture sector in terms of species and technologies. No target has been quantified by the government, but the seafood industry produced estimation numbers of future seafood productions accounting for these governmental priorities and found an expected growth of salmonids production of 2-4% depending on how well and how fast the environmental issues are addressed, and an expected annual production of cods of 30000 tons/year in 2030 and mussels from IMTA of 2000 tons/year in 2030 (Olafsen *et al.*, 2012).

Step 2.2: Defining scenarios

The three developed scenarios are described below:

- *Business-as-usual scenario (NO-BAU)*: No important measure is taken to implement the strategies. Environmental issues are assumed to be solved progressively, achieving an annual increase of salmonids from sea cages of 3%. No increase in the other categories.
- *Scenario 1 (NO-S1)*: Norwegian decision-makers implement strategic incentives for diversification of the aquaculture production technologies, thanks to a quick reduction of environmental issues. Consequently, salmonids in sea cages have an annual increase of 4%, and innovative salmonids technologies have an important annual increase over the whole period of 20%. IMTA has an increase of 15%.
- *Scenario 2 (NO-S2)*: Norwegian decision-makers implement strategic incentives for diversification of the aquaculture production species. A slow reduction of environmental issues linked to salmonids involves an increase of salmonids in sea cages of only 2% annually. White fishes and IMTA productions undertake an annual increase of 5% and 25% respectively. The other salmonids' technologies have a modest increase of 10%.

As capture fisheries are expected to remain stable in the future due to the introduction of new regulations to control fish stocks, no increase is modeled for any of the capture categories in any of the scenarios. All chosen technological factors are available in **Supplementary Information of Paper V**.

Step 2.3: Adapting the Asiafish model

As explained in section 4.4, the technology used to produce a food item does not influence consumers' purchasing decisions, and therefore only 6 demand categories (including processed seafood) are needed in the Norway case study to correspond to the 12 supply categories defined in section 5.1.2. This is illustrated in Figure 20.

Figure 20: Structure of the AsiaFish model adapted for Norway, with the different supply, demand and matching categories, i.e. trade. Excerpt from Paper V.

Data from Statistics Norway, the Norwegian Seafood Council and Fiskeridirektoratet were used to populate the model in terms of seafood production and trade as well as economic and demographic inputs (Fiskeridirektoratet, 2017; NSC, 2019; SSB, 2019b). Table 11 and Table 12 present the seafood demand-supply balance in Norway for the 12 supply categories and the 6 demand ones. The reader is invited to refer to **Paper V** for details about how it was built.

Elasticities of demand, supply and expenditure were determined in a literature review conducted on Norway and the EU in general because of the integration of the European market for some species (Nielsen et al., 2009). When several potential sources were found for the same elasticity, averages were taken. In general, own-price and expenditure elasticities were found differentiated by species group for Norway or the Nordic countries. Otherwise, countries such as the United Kingdom were used as a proxy. As for Singapore, non-substitutability and non-complementarity were assumed across groups, and therefore all cross-price elasticities were set to zero, and perfect substitution was assumed within groups and therefore supply elasticities were all set to zero. A comprehensive description of sources and assumptions made to build the model is available in **Paper V** in **Supplementary Information**.

Table 11: Seafood balance for Norway in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories. Excerpt from Paper V.

	Salmonids					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
	Sea cages	RAS	Offshore	IMTA	Capture	Sea cages	Capture	Capture	Capture	IMTA	Capture	
<i>Production</i>	1,290,376	13,058	0	0	2,112	1,623	812,704	791,955	4,286	0	23,589	1,234,735
	Salmonids					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
<i>Consumption</i>	22,209					102,409		857	4,148		448	164,762
<i>Export</i>	861,920					245,720		79,027	553		1,350	1,169,262
<i>Import</i>	290					332		144,388	477		181	99,289
<i>Intermediate</i>	421,968					466,530		856,459	85		21,971	-

Table 12: Seafood balance for Norway in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories. Excerpt from Paper V.

	Salmonids					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
	Sea cages	RAS	Offshore	IMTA	Capture	Sea cages	Capture	Capture	Capture	IMTA	Capture	
<i>Production</i>	10,570,912	97,346	0	0	17,283	3,793	1,899,476	834,391	8,962	0	185,259	6,805,529
	Salmonids					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
<i>Consumption</i>	237,948					266,820		974	7,088		3,308	1,849,735
<i>Export</i>	5,929,634					424,448		38,400	4,172		25,624	5,507,766
<i>Import</i>	1,119					3,509		178,282	2,397		5,774	551,973
<i>Intermediate</i>	4,521,004					1,215,511		973,299	145		162,101	-

Step 2.4: Generating scenarios

The scenarios described in step 2.2 were generated using the Asiafish model. The results obtained are available in **Supplementary Information of Paper V** and are discussed in the following paragraph.

Step 2.5: Analyzing the scenarios

A consistency check was conducted on the results obtained, and it was concluded that the results were consistent with the expected outcomes. The variations of quantities produced, imports, exports and consumption corresponded to the implemented changes, and the prices variation within the time-scope was considered reasonable enough to be realistic. A detailed analysis of the prices obtained is available in **Paper IV**.

Figure 21: Total domestic production, consumption and imports of fresh fish and processed fish in Norway for the three scenarios during the period 2017-2040; the difference between the total domestic demand and the cumulated stacked curves equals the exports. Excerpt from Paper V.

Figure 21 gives an overview of the total Norwegian domestic supply, demand and imports in terms of seafood during the period 2017-2040. An important difference between the demand curve and the cumulated stack curves can be observed in the three scenarios, illustrating that Norway seafood industry remains a net exporter in all scenarios developed in this study. The fresh seafood production increases in the three scenarios while the processed fish production remains stable. As explained in step 2.2, no increase is modeled for the capture sector, and therefore the witnessed increase originates solely from seafood farming. Looking at aquaculture in particular, Norwegian production

increases from 1 million tons in 2017 to 2.5/4/2.1 million tons in NO-BAU/S1/S2. This illustrates how the rapid solving of the environmental issues in NO-S1 engenders a much more drastic increase in the seafood production than in the other scenarios. These numbers are all within the range of production expected by the industry (Olafsen et al., 2012). The seafood consumption is found to increase in all scenarios, and by 13%/19%/16% in NO-BAU/S1/S2. Imports are and remain very limited in all scenarios.

Due to the extreme quantities of salmonids produced in sea cages, the other species and technologies in aquaculture remain almost invisible in the graphs of Figure 22 despite an important increase for some of them. Figure 23 therefore displays the production of all aquaculture categories with a logarithmic scale. The important increase of salmonids in RAS is again visible for both explorative scenarios. In NO-S1, it appears that the production of salmonids in offshore systems also enters the production mix, and reaches 10000 tons in 2040. In NO-S2, the production from white fishes and mollusks increases both notably, with 5000 and 3600 tons/year, respectively.

In the light of these observations, it appears that Norway is likely to maintain its place as an important international producer of salmonids in all scenarios thanks to a constant increase in production. NO-S1 is the only scenario where the total production in 2040 exceeds the average prediction of the industry, which was 3 million tons/year. Regarding the willingness to diversify the aquaculture industry in terms of technologies, the important introduction of RAS in NO-S1 and the fair development of RAS and offshore systems in NO-S2 are likely to help reducing escapes and disease propagation problems, though to a limited extent as the production in sea cages remains dominant and continues to increase in both scenarios. The diversification in terms of species is far below the expectations of the industry made in 2012, which suggests that these predictions were based on data/considerations that are not relevant anymore and should be re-considered. For instance, the production of white fishes was booming at the time, with 21000 tons/year in 2010. However, it dropped to 4 tons/year in 2015 due to issues such as high larval mortality rates and important escapes levels that could not be addressed (Brown et al., 2003; Moe et al., 2007). It is therefore not surprising that the white fishes production does not reach the expected levels.

Therefore, it seems that remaining a major aquaculture producer will be easy but diversifying its aquaculture production will be a great challenge for Norway. Meeting its goal of developing the aquaculture industry in a sustainable way might require important financial investments that would create more drastic incentives in developing other production categories than salmonids in sea cages, and might require a major technological breakthrough.

Figure 22: Domestic seafood production (a) and annual distribution (b) for each of the species and technologies and for the 3 scenarios in Norway, and the years 2017, 2030 and 2040. Excerpt from Paper V.

Figure 23: Domestic aquaculture production for each production category in the 3 scenarios, and the years 2017, 2030 and 2040 for Norway (logarithmic scale). Excerpt from Paper V.

A sensitivity analysis was conducted, available in the **Supplementary Information of Paper V**. The AIDS parameters, the CES/CET and the demand and expenditure elasticities were selected as the most uncertain parameters of the study. By making them vary by +/-10%, it was found that the Norwegian model seems more sensitive in general than the Singaporean one. NO-S1 was especially sensitive to change in expenditure elasticities and to CES/CET, and NO-S2 was highly sensitive to all tested parameters.

5.2.4 Step 3: LCA methodology application

Goal and scope definition

The goal of the macro-scale LCA on Norway aquaculture was to compare the evolution of the normalized environmental impacts of the different scenarios construction in step 2 through the period 2017-2040. The same two Feed options than in the Singaporean assessment were included and compared for the same reasons, which are (1) increasing the part of trimmings in the manufacturing of FMFO and (2) replacing FMFO by insect-based meal and algal oil.

The FU was defined as “the average production (over a year) of 1 ton of edible seafood in Norway in the period 2017-2040”. The system boundary contained six main elements as described in Figure 10, and harvesting (boats and fuel), cages/nets cleaning, boats manufacturing and materials, generators manufacturing and materials, use of medicine, drugs and vaccines, infrastructures and consumables transport to the farms, transport of the final product to retailer and to consumer, retailing and cooking were excluded. Salmonids and white fishes needed post-farming processing due to the size of the sold fishes. All the impacts at farm gate were divided by an edible fraction to obtain the impacts per mass of edible seafood. These edible factors varied depending on the species. The multifunctionality was handled similarly than in the Singapore case study, i.e. system expansion was prioritized, but if the co-products were conventional ways to fulfill the co-functions created, allocation based on gross energy was applied. As recommended in section 4.5.1, consequential modeling was used.

Life cycle inventories

Due to temporal restrictions, no primary data could be collected in Norway. Consequently, the LCIs were built solely based on existing literature. Thanks to the multiple existing LCA studies on Norwegian aquaculture, the LCIs of most production categories could be built on Norwegian data. The most optimized systems were prioritized to build the inventories, as it was assumed the best representation of current and future practices. For details about the sources and the assumptions used to build the LCIs of Norwegian aquaculture, the reader is invited to refer to **Paper V**.

The consequential version of the ecoinvent v3.5 database was used. However, as for Singapore, the average electricity mix was used instead of the long-term marginal one,

because it was assumed that the increase in aquaculture production in Norway was associated to no structural changes in any country part of the foreground system, i.e. Norway (production of fishes, fingerlings, marines-based ingredients and aquafeed), France (production of all plant-based ingredients except soybean meal) and Brazil (production of soybean meal). Finally, no changes in the production of other countries were modeled because global food needs are constantly increasing, and additional seafood exported from Norway is likely to cover the growing demand for salmonids in transitioning countries, where incomes together with salmonids demand are increasing. It is possible that this increase in salmonid consumption replaces the consumption of other protein products, but the data available on the topic were too scarce to allow any quantified inclusion of such speculations in the current study. Some processes were adapted from the Agri-footprint v4.0 with ecoinvent inputs/outputs for homogeneity (Durlinger et al., 2017; Wernet et al., 2016). The software Simapro v9.0.0.49 was used to construct the model and to assess it (PRé Consultants, 2018).

These inventories were generated for the reference year 2017. Adapting them to the period 2018-2040 required to apply changes to the following parameters and processes: the feed production, the FCR, the water and energy use during the farming phase and the electricity grid mix. Table 13 summarizes and describes the selected parameters/processes with the corresponding changes.

Table 13: Changes in the life cycle inventories of Norway between 2017 and 2040. Adapted from Paper V.

Change type	Parameter/process impacted	Change within 2017-2040
Feed ingredients	<i>Feed option 1</i> Fishmeal and fish oil production	Part of FM (FO) produced from by-products increases from 19.4% (28,1%) in 2017 to 70% (80%) in 2040.
	<i>Feed option 2</i> Feed pellets production	Salmonids: 100% of FMFO replaced by insect-based meal and algal oil in 2030. White fishes: 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 5 to 15% depending on technology maturity ¹ .
	Energy need	Decrease by 5 to 15% depending on technology maturity ¹ .
	Feed conversion ratio	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	Hydropower remains predominant but small introduction of wind power (IEA, 2016)

¹: Determined based on the literature and my own expert opinion.

Life cycle impact assessment

The same set of impact categories were assessed for Norway than in the Singapore case, with the same methods (see Table 9).

5.2.5 Step 4: Results of the national-level assessment and interpretation

Figure 24 presents the results of the application of the framework to Norway; it displays the evolution over 2017-2040 of the impacts per yearly-averaged ton of edible seafood produced in Norway for the 3 developed scenarios, hereafter referred to as the “normalized impacts”.

General trends

Figure 24 shows that in general, in the Norwegian case study, the temporal variation of the impacts per averaged ton of edible seafood depends more on the Feed option than on the scenarios. Limited differences between scenarios in terms of production mixes explain this result (described in step 2 and seen in Figure 22). Generally, temporal variations of the normalized impacts are small with Feed option 1 (max +/-15% compared to 2017), and quite drastic with Feed option 2. The changes are especially important between 2020 and 2030, the period during which the novel ingredients are introduced. Most impact categories see their normalized scores increasing through the years due to the generally higher impacts per unit of insect-based meal and algal oil compared to fishmeal.

The biggest relative increase is witnessed for freshwater ecotoxicity, and linked to electricity production impacts. Indeed, the manufacturing of the novel ingredients requires more electricity per unit than traditional ones and the Norwegian electricity mix has growing toxic impacts per unit during 2017-2040 due to the introduction of wind power replacing the very environmental-friendly hydropower. However, exceptions include NPPU and eutrophication, which decrease radically with Feed option 2.

The larger difference between scenarios is observed for freshwater eutrophication and NPPU, for which NO-S1/S2 are lower than NO-BAU by ca. 20%, and for freshwater ecotoxicity and ionizing radiations, for which the explorative scenarios are higher by up to 45%. This is directly linked to the increasing proportion of production in RAS compared to sea cages, this system being a closed one with low eutrophication impacts, but important electricity needs that involve a non-negligible toxicity burden (see above paragraph).

Focus on climate change

Climate change impacts are almost equal in all scenarios, with both Feed options and through the entire time-scope. The scores belong to the range 5-6 tons CO₂-eq per average ton of edible seafood produced, which is comparable to results obtained in Liu *et al.* (2016), but slightly higher than Winther *et al.* (2009) (2.5-4 tons CO₂-eq/ton-edible-seafood).

Figure 24: Evolution between 2017 and 2040 of the characterized scores corresponding to 1 yearly average ton of edible seafood produced in Norway in the 3 scenarios and the 2 different feed options, for the 18 impact categories of IMPACT World+ midpoint and net primary production use (A to S) and for the 2 areas of protection of IMPACT World+ endpoint (T and U). Excerpt from Paper V.

Focus on eutrophication

As mentioned already in the previous paragraph on general trends, eutrophication is one of the only impact categories where a noteworthy difference between scenarios is observed, due to the introduction of RAS in NO-S1 and NO-S2. However, the Feed option also influences highly the scores of this impact category, and Feed option 2 induces a much higher decrease than Feed option 1. Indeed, Feed option 1 has many advantages but implies no decrease of eutrophication as the actual composition of the diets and the FCR do not change compared to 2017. Contrarily, the change of ingredients in Feed option 2 entails an important decrease of eutrophication.

Focus on resources

In this case study, resources use are found to depend solely on the Feed option choice. Water scarcity, fossil and nuclear energy use, mineral resource use and land occupation are higher for Feed option 2, but NPPU and land transformation have lower scores with Feed option 2. The production of co-products during insect-based meal and algal oil manufacturing explain the decrease in land transformation, due to the use of system expansion and the associated avoided production of animal feed. The complete removal of FMFO from the salmonids diet in Feed option 2 explains the decrease in NPPU, and is even associated to no NPPU impacts at all from feed production from 2028, which explains why normalized scores of NPPU become negative around that date due to the use of post-farming trimmings in the FMFO industry (i.e. avoided production of fresh fish).

Limitations of the study

Uncertainties and sensitivities of the Norwegian results are in general similar to those of the Singaporean results, as they are mainly linked to the prospective nature of the study (see section 5.1.6). Additionally, the electricity mix seems to be a sensitive parameter as a small change over the years implies important changes in impacts for the production category using electricity from the grid (e.g. RAS).

5.2.6 Recommendations

Based on the results of the framework and their analysis above, recommendations for Norwegian decision-makers are provided.

The analysis of the case study's results suggests no clear preference for a scenario over another, as the difference between scenarios' scores is very small. Therefore, few recommendations can be produced regarding which scenarios Norway should get inspired from to remain an important player on the global aquaculture stage while diversifying the production to build a more sustainable sector. The analysis of the environmental impacts of the desired new production categories revealed that some of them have higher environmental impacts per unit produced than salmonids in sea cages, such as the farming of white fishes. Contrarily, salmonids produced in RAS and

integrated with mollusks in IMTA seem to offer important decrease of several impact categories. Therefore, Norway should consider implementing strong incentives to increase the production of salmonids in RAS and the IMTA systems in general. Regulations can be produced to encourage new aquaculture companies to prefer onshore RAS technologies. On another level, existing producers of salmonids in sea cages should be highly encouraged to add mollusks production to their farm through the addition of an IMTA module, e.g. through a decrease of taxes or governmental help to build such additional infrastructures. However, genuine diversification of the Norwegian aquaculture in terms of species and technologies is not truly reached in any of the 3 scenarios developed in this study, as discussed in step 2.5 and section 5.2.3. This reveals that the economic conditions structuring the current Norwegian aquaculture do not allow such drastic transformation, hence the need for additional changes than a simple increase in production to change the aquaculture landscape in Norway. Additional economic studies are needed to define which factors should be influenced to allow the Norwegian aquaculture to undergo the willing change, such as imports/exports factors or local expenditure behaviors.

There is an important difference between the obtained scores for Feed options 1 and 2. Replacing the FMFO by novel ingredients (i.e. Feed option 2) seems to cause an increase of most impact categories' scores through time, but an important decrease of NPPU, eutrophication and land transformation. Increasing the part of trimmings in FMFO manufacturing (i.e. Feed option 1) induces little variations on most impact categories, except NPPU that decreases (but less than with Feed option 2). Therefore, overall, Feed option 1 appears as the best solution (among those tested in this study) to limit the environmental impacts of aquaculture production in Norway per unit of edible seafood produced. Norway is an important FMFO producer, and could therefore implement new regulations imposing a minimum proportion of trimmings in its FMFO manufacturing.

5.3 SIMILARITIES BETWEEN THE TWO CASE STUDIES

5.3.1 Dominance of feed production

Feed production was found to dominate the environmental impacts of most production categories in many past LCA studies (see section 3.2.2). The micro-level study (step O) of the Singapore case study draws the same conclusion. It is therefore not surprising to find that the Feed option is also very important in the large-scale studies, for both Singapore and Norway. When looking at the evolution through time, Feed option 1 is in general found to stabilize or decrease the environmental impacts per averaged ton of seafood produced while Feed option 2 is found to increase them. However, the novel ingredients introduced in Feed option 2 are at an early stage of maturity, and their production is not optimized yet. While a gradual optimization of the manufacturing of these ingredients has been modeled in this study, such changes are highly uncertain and it is possible that the manufacturing of insect-based meal and algal oil becomes more

environmental friendly in the future than what has been assumed in this study, which might reduce the environmental gap between the two Feed options assessed.

Additionally, a large-scale adoption of Feed option 1 (i.e. increasing the proportion of trimmings in FMFO production) involves some challenges. First, the quality of the FMFO might be degraded when the proportion of trimmings increases relatively to fresh fish, due to the difference in fats and nutrients content of such products. Using trimmings implies that the fish species and the fish parts are not completely selected by the FMFO manufacturers, and may not contain the characteristics required for high-quality FMFO. Furthermore, despite all its environmental benefits, this Feed option entails no decrease of eutrophication. This impact has historically been considered as the most important risk of aquaculture (Goldburg and Naylor, 2005) and can be decreased only if the diet composition is changed or the FCR is cut down. This can be done by changing the ingredients or the feed management to provide farmed specimens with only the strict minimum amount of nutrients needed for their healthy growth. To conclude, the combination of a highly optimized diet composition to reduce feces, optimized feed management to reduce uneaten feed and the highest possible use of trimmings in the FMFO production seems to be a beneficial option for reducing the environmental impacts in Singapore and Norway.

5.3.2 Climate change mitigation perspective

In the Paris Agreement of the COP 25, both Singapore and Norway set climate change mitigation targets. Singapore aims at: (1) reducing its emissions intensity by 36% below 2005 levels by 2030, and (2) stabilizing the yearly emissions of GHG by the same year (MEWR, 2018), while Norway is willing to reduce its total climate change impacts by 40% before 2030 (The Mission, 2019).

The first goal of the Singaporean government regards emissions intensity, i.e. the emissions of GHG per unit of production. Among the scenarios and options assessed in the Singaporean case study, impacts per ton of aquaculture production can decrease at most by 7% between 2017 and 2040 (SG-BAU with Feed option 1). Even considering a decrease prior to 2017, this seems far from the Singaporean target. The second goal of the Singaporean government concerns the total emissions of GHG, which are found to increase for the aquaculture sector in both explorative scenarios, while it remains stable with SG-BAU. This is due to the important increase in production that is not compensated by a decrease in emissions intensity as mentioned before. Figure 25 illustrates that growth and puts it in perspective with the increase of production in each scenario (secondary axis). Concerning Norway and its climate change target, the normalized impacts per unit of edible seafood are found to remain stable during the whole period, while the total production increases in all scenarios. Therefore, as illustrated in Figure 26, the total impacts of the aquaculture industry increase between 2017 and 2040, whatever scenario is chosen.

However, the current study adopts a semi-consumer perspective in the sense that it accounts for emissions during the whole life cycle (not only the ones occurring in Singapore or Norway), while the targets of the Singaporean and Norwegian governments relate only to local emissions. For Norway, where most of the feed is produced locally as well as most of the energy and equipment, the change of perspective might have a limited influence on the results. However, for Singapore, this can make an important difference because none of the other stages than farming occurs in the city-state. When only impacts linked to the farming stage are included (and not the full life cycle), the prospects are even worse because climate change impacts per unit of seafood produced are at best stable and at worst increasing by 40%, depending on the scenario. Combined with the increase in production, this suggests that the aquaculture sector would not participate to the desired reduction of Singaporean emissions intensity nor to the stabilization of emissions by 2030 if the Singaporean government is willing to achieve its “30-by-30 policy”.

Hence, for both Singapore and Norway, it seems that the aquaculture industry would not contribute to reaching the climate change targets set by the two governments if they are willing to persevere with their respective aquaculture growth policies. They would therefore need to decrease GHG emissions in other sectors more drastically to have a chance to reach their climate change mitigation targets at national level.

Figure 25: Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Singapore, with the total production of edible seafood on the secondary axis in tons per year. Excerpt from Paper V.

Figure 26: Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Norway, with the total production of edible seafood on the secondary axis in tons per year. Excerpt from Paper V.

Nonetheless, the increase of aquaculture production obtained with the policies would either participate in reducing the global hunger issue, or replace the production of other food in another country. Both options lead to burden-shifting of impacts, but might create overall a more sustainable global food system. The first option would participate in decreasing social burdens, while the second is likely to engender a decrease of GHG emissions somewhere else. It is therefore necessary to conduct full consumption-based studies that account for all these consequences and assess comprehensively the sustainability of the aquaculture sector (c.f. discussion in section 6.3.3).

5.3.3 Eco-efficiency vs. Eco-effectiveness

The first target of the Singaporean government for climate change mitigation is expressed in terms of reduction of emissions intensity (see section 5.3.2). This reflects eco-efficiency, which aims at reducing the impacts per unit produced, usually by minimizing consumption and wastes. Historically, eco-efficiency has been at the heart of corporate and industry sustainability strategies (Young and Tilley, 2006). However, reducing the impacts per unit produced does not necessarily mean that the total impacts associated with the assessed function decreases. An increase of eco-efficiency can have unattended consequence such as behavioral changes, due e.g. to improved accessibility to the product or service, that consequently increase its demand. This increased demand can counteract the environmental impact reduction, i.e. offset the gains in eco-efficiency. Environmental economists call that the “rebound effect” when the environmental benefits are lower than expected, or even the “backfire effect” when the environmental impacts increase compared to the starting point (Hertwich, 2005). This illustrates that eco-efficiency is an important pre-requisite to sustainable consumption and production but it is not sufficient

to ensure a sustainable development of industries. All the consequences of a change should be considered for a comprehensive assessment of a product or system sustainability. From this observation, the complementary concept of eco-effectiveness of products and systems emerges, which aims at creating an industry that is regenerative, inspired by cradle-to-cradle⁴ considerations instead of cradle-to-grave ones (Bjørn and Hauschild, 2013; McDonough and Braungart, 1998). While eco-efficiency ensures relative sustainability, products and systems that are eco-effective might lead to absolute sustainability.

In this project, climate change impacts per unit of seafood produced are found to decrease only in an anecdotic way in both assessed countries (maximum 7% for Singapore and 8% for Norway). Nonetheless, it is found that the increase in domestic production of seafood in the explorative scenarios contributes to change both Singaporean and Norwegian eating habits by increasing their total consumption of seafood (see step 2.5 in sections 5.1.4 and 5.2.3). It is likely that this would replace the consumption of other animal protein sources, whose production might therefore decrease. Even if seafood production is not environmentally neutral, it is usually associated to lower environmental impacts than other animal production, in particular beef. In their LCA study of beef production in Thailand, Ogino *et al.* (2016) found climate change impacts twice higher per ton of edible product than the highest environmental impacts associated to seafood in the Singaporean study (edible fraction: taken from University of Tennessee Institute of Agriculture, 2019). Production of beef in Scandinavia was found to have climate change impacts in the range of 34-44 tons CO₂-eq/ton-edible-beef in Mogensen *et al.* (2015), which is 6 to 9 times more than the impacts found for edible seafood in this study for Norway (edible fraction taken from University of Tennessee Institute of Agriculture, 2019). If the increasing production of seafood in the explorative scenarios participates to replace some of the consumption of beef by seafood, total climate change impacts of food consumption in Singapore and Norway are likely to decrease through the years. Therefore, the production of seafood in Norway and Singapore may not become way more eco-efficient through the years, but it might increase the eco-effectiveness of the food sector as a whole, which ultimately brings us closer to absolute sustainability of the global food system.

⁴ However, eco-effectiveness is not equivalent to the “cradle-to-cradle concept” (C2C). They are only linked through their approach to sustainability.

Chapter 6 OPERABILITY & RELEVANCE OF THE FRAMEWORK

6.1 OPERABILITY CHECK & IMPROVEMENTS FOR BETTER USABILITY

The framework developed in this PhD project has been successfully applied to two case studies with very different seafood production profiles. This contributes to proving that the framework is adaptable to any country, policy and time scope. This flexibility is a valuable asset for potential future practitioners that are willing to apply the framework to new cases.

Yet, some obstacles remain for an easy application of the framework. They are described and discussed in the following paragraphs together with suggestions about how relevant stakeholders can address them. These improvements would make the current framework easier to use and improve its reliability by reducing the uncertainty of its results.

First, representative data were not always available for the specific countries and with the right species/technologies differentiation for the study. This required adapting available data to construct inputs needed in the framework based on assumptions. For instance, in the Singaporean case study, seafood production, consumption and trade data needed for the construction of the scenarios (step 2) were not readily available with adequate species differentiation. Therefore, data from the FAO were adapted using literature sources and assumptions to produce best estimates. Similarly, few elasticities were found for seafood in Singapore during the review of the literature (c.f. section 5.1.4). The ones found were not adequately differentiated and thus general elasticities for seafood products were used instead. This approach decreases the preciseness of the inputs and thus increases the uncertainty of the results. Therefore, there is a need for a more transparent communication of national and regional statistics as well as general industry data that could be useful for research and policy support. Additionally, there is a need for more economic studies on aquaculture related topics. Consumers' behaviors and habits related to different food items should be analyzed and demand, supply and trade elasticities should be calculated, both with a high level of differentiation. This would allow a better understanding of the food system dynamics and help identify reliable solutions to tackle global nutrition issues.

Secondly, current LCIA methods have missing pathways for impacts specific to aquaculture, as already identified in the literature review (see section 3.3.4). A comprehensive set of existing impact categories were assessed when applying the framework to the case studies, but today, LCIA methods do not cover all impacts linked

to aquaculture, such as escapes or deterioration of the seabed due to the presence of farms. For a comprehensive assessment of the aquaculture sector, such potential degradation in biodiversity should be included. Therefore, LCIA methods' developers and ecosystems specialists should combine efforts on the development of a comprehensive set of impact categories linked to seafood production. For instance for the escapes issue, the ecological impacts of the presence of farmed species in natural ecosystems should be quantified by ecosystem specialists before LCIA developers can implement it to their methods. This is an important step on the path to more comprehensive assessment of environmental sustainability of these systems.

Thirdly, in its current state, the application of the framework requires trans-disciplinary knowledge that is crosscutting several fields, including LCA and economic theories. Such transversal knowledge may be difficult to secure for potential users of the framework/analysts. Collaboration between different fields might be a relevant strategy in this situation. Based on these observations, the development of economic models that are more user-friendly would be valuable. For example, a software could be created where the practitioner would first enter the production categories he/she wants to include and the model would be automatically adapted to the new structure. Then the needed inputs (i.e. quantities and value of the production in the first year, elasticities, population growth, inflation rates, etc) could be entered in the form of a list or table to fill. This would make the framework more accessible to practitioners with limited economic and modeling expertise. Regarding the LCA part, the LCIs construction and modeling could be simplified by creating standard, pre-built LCIs for all common technologies and species groups. The practitioner would only have to enter the quantities corresponding to its inputs per ton of seafood produced (e.g. amount of water, feed, electricity, fuel for the boats, nets, ponds, etc) as well as choosing the specific characteristics of the system (e.g. composition of the food, origin of the electricity, size of the ponds, etc) and LCIs would be created as a list of tables corresponding to each process with inputs, outputs, emissions and avoided production, ready to be implemented into an LCA modeling software. This would make the framework more accessible to practitioners with limited LCA skills.

Finally, another way to make the model easier to handle by future practitioners from different backgrounds would be to integrate an environmental module within the economic equilibrium model. The practitioner would still have to conduct LCAs of the different production systems in a separate and specialized software, but the results of the impact assessment could be injected in the economic model as inputs and used to create acceptable thresholds. This would facilitate the interpretation phase as the results of the scenarios and the LCA would be produced simultaneously, and the environmental impacts could be used directly as optimization criteria in the design of the scenarios. Other parameters could be used as optimization criteria, such as LCI flows, and linked to economic parameters. For instance, it would be convenient to link the need in land occupation during farming stage per ton of seafood produced to a maximum available surface that the local government would be willing to allocate to food production, or to

a specific price of land that would vary depending on the location and the type of land. The energy sector has already implemented environmental impact calculation modules in complex economic models, which could be used as an example for similar adaptations in the food sector (Astudillo et al., 2018). This would allow linking the different steps of the framework in an intrinsic and more consistent way. Even though the final economic-environmental model would be more complex in the sense that it will have more parameters and equations, each step would be simpler and the interpretation would be more integrated and intuitive.

In an even further future, all the phases of the LCA could be incorporated in the economic model for full integration of the two tools. However, how to handle the LCI and LCIA databases and their updates inside another model than specialized LCA software is still to be determined.

6.2 RELEVANCE FOR POLICY-MAKING

The application of the framework to the two case studies allowed the production of various recommendations to local policy-makers and other aquaculture stakeholders. Based on the Singaporean case study, regulators received scientific evidence regarding which species and technologies to encourage if the policy “30-by-30” is to be reached with a minimum of environmental and economic drawbacks. It was also determined that the desired increase of food production applied on the aquaculture sector will increase the total climate change impacts of that industry, which will then need to be balanced by the reduction of climate change impacts in other sectors to reach the engagement of stabilizing GHG emissions in Singapore by 2030 (country commitment as part of the Paris Agreements). The Norwegian study revealed that the current state of the industry and the modeled economic conditions do not allow the combination of a constant increase of seafood production and a diversification of the sector in terms of species and technologies. To reach both objectives, stronger incentives need to be implemented than a simple increase of production, as the economic situation needs to be changed more deeply, e.g. through influencing imports/exports dynamics or consumption behaviors.

Overall, some concrete recommendations were produced based on the application of the framework to the two countries. They illustrate what the developed framework can provide and support, even though it is important to note that every case study has its own specificities and would lead to its own specific set of conclusions and recommendations. Nonetheless, large uncertainties accompany the prospective nature of the study and results should always be analyzed and considered in perspective with their limitations. It should be remembered that this framework does not produce a forecast of the policies implications and does not intend to give accurate predictions of the future. It produces an overview of potential trends and tendencies that the implementation of

the policy can have, in the limit of the uncertainty associated with the input data and the applicability of the models' theories to the specific case.

6.3 IMPROVEMENT POTENTIAL DUE TO CURRENT SCOPE LIMITATIONS

As testified by its relevance for policy-making, the framework developed in this PhD project is a major first step in sustainability assessment of aquaculture policies. However, there is still potential for improvement and other steps are needed to ameliorate the scope of the framework and its associated models, and to increase the accuracy of the results and thereby the reliability of their support to policy-makers. In this section, the main methodological limitations of the framework are listed together with recommendations about how to address them through the implementation of new or different methods.

6.3.1 Including the impacts of antimicrobial resistance

One aspect not currently considered in the framework is that aquaculture production might have impacts on global human health because of its use of antimicrobials. It has been proven that antimicrobials use in aquaculture leads to antimicrobial resistance (AMR), which is considered by the WHO as one of the most serious threats to global health currently (Santos and Ramos, 2018; WHO, 2018). AMR impacts on human health are not currently assessed in LCA (**Paper IIa**), but quantifying risks of AMR has already been done in the literature using another tool: quantitative microbiological risk assessment (RA) adapted to AMR (also called antimicrobial resistance risk assessment or ARRA; Claycamp 2015).

As for today, there is no study in the literature combining specifically ARRA and LCA. However, the combination of LCA and RA (in general, not only ARRA) has been recognized as allowing for more comprehensive assessments of multidimensional issues (Cowell et al., 2002; Owens, 1997). Olsen *et al.* (2001) concluded that RA and LCA are not substitutable due to their differences in aims and scopes. Therefore, some practitioners tried to combine the two assessment methods. For example Bare et al (2006) integrated human health RA and human health LCA, and highlighted that with only LCA, impacts on local populations might not be appropriately assessed, whereas stand-alone RA might have missed burden-shifting of impacts to other populations. In another study, Kobayashi et al. (2017) converted the results of a RA on different air quality scenarios in DALY in order to compare them directly to their corresponding LCA results. The conclusions of the study changed compared to the RA or the LCA alone, emphasizing the high value-added of conducting both methodologies for better-informed decision-making.

Overall, several approaches have been identified to combine the two methodologies. One of them is the RA-complemented LCA, which was described by Grieger *et al.* (2012) as

the only approach to genuinely combine RA and LCA for nanomaterials at the time. It implies to apply RA in parallel to LCA on the life cycle stages that are relevant and then analyze the results together. This approach has been commonly used, as for example Linkov and Seager (2011) who coupled it with multi-criteria decision analysis for an easier interpretation of the results by attributing a weighting score to each assessment, and obtained comparable results than if calculated in two separate assessments. Another approach is to integrate RA in the LCIA phase of the LCA as an additional impact category, by creating new impact pathways inspired by those of chemicals in e.g. USEtox (Rosenbaum et al., 2008). However, Harder et al. (2016) found that important changes in the RA framework are necessary for that purpose, leading to non-negligible changes in its results. They concluded that the direct integration of the two tools might be problematic for maintaining results quality. Thus, the approach of “RA-complemented LCA” seems more adapted to the combination of RA and LCA.

Recently, Dong *et al.* (2018) highlighted the benefits of combining LCA and RA for policy-making. Therefore, the combination of an ARRA to the LCA of this framework seems especially beneficial. It would allow including AMR considerations in the decision of the more preferable option. This would require using a large-scale RA to fit the national level of the assessment. This has already been done in the past for specific situations and countries e.g. for assessing the risks of climate change on Austrian forests at national level (Lexer et al., 2002). To base the assessment on empirical data, fish samples would need to be collected in as many farms as possible, to be analyzed in laboratories where the prevalences and concentrations of bacteria presenting AMR would be determined. Samples and therefore experimental data from all life cycle stages would be needed. This would increase the time and budget requirements of the study drastically compared to a normal LCA. Another difficulty would be related to the large amount of bacteria types and antimicrobials to include in the study, as AMR is detected for specific bacteria and antimicrobials combinations in each sample. Therefore, for an assessment of general AMR, multiple combinations of bacteria and antimicrobials would need to be tested, which would again multiply accordingly the costs and time requirements of the study. However, considering the importance and urgency of the AMR issue according to the WHO (WHO, 2018), the inclusion of ARRA in the framework is a necessity to tackle all important issues linked to aquaculture.

6.3.2 Including economic and social sustainability

As introduced in chapter 1, sustainability includes three dimensions: economic, social and environmental. This PhD project focused on the environmental dimension, because the two others cannot be sustained unless the environmental sustainability is secured (as explained in chapter 1). However, sustainability cannot be reached unless the three dimensions are considered. Therefore, to broaden the scope of the existing framework, the LCA should evolve into a life cycle sustainability assessment (LCSA). This is an interdisciplinary framework that aims at accounting for the 3 pillars of sustainability in an integrated scheme, and has usually been defined as $LCSA = LCA + S-LCA + LCC$

(Kloepffer, 2008), where LCA is an environmental life cycle assessment (referred to as E-LCA in this sub-section to avoid confusion), S-LCA is a social life cycle assessment and LCC corresponds to an LCA-type life cycle costing.

Despite being researched since the mid-2000s (see e.g. Dreyer, Hauschild and Schierbeck, 2006), S-LCA is still in a development stage compared to E-LCA and there is a lack of general standardized indicators (Kühnen and Hahn, 2017). Still, S-LCA has been applied on various case studies and assessed indicators as various as child labor, cultural heritage or corruption, as found in the literature review by Kühnen and Hahn (2017, 2018). When it comes to aquaculture production, various social impacts would be interesting to assess and include in the study. Among them, problems related to workers would be relevant, such as fair salaries, hours worked per day or health and safety in the workplace, due to the labor-intensive nature of this industry and the potentially hazardous conditions the workers can be put in due to the offshore situation of the farms. Assessing impacts related to society would also be particularly interesting, such as contribution to economic development and technology development, due to the sectoral approach of the study that may induce large-scale impacts on society.

The LCC used in LCSA goes beyond a simple economic cost calculation as it includes end-of-life and use phases and hidden costs (Kloepffer, 2008). However, the trend is to move towards a “true” economic counterpart of E-LCA to assess the economic sustainability pillar in LCSA, called economic life cycle assessment (EcLCA, as introduced by Neugebauer, Forin and Finkbeiner, 2016), which would replace LCC. In EcLCA, similarly to E-LCA, economic aspects would be linked to impacts and damages through impact pathways, and assessed through the whole life cycle of the product or system (Neugebauer et al., 2016). Impact categories could include profitability, productivity or business diversity, and would lead to two new AoP, namely wealth generation and economic stability (Neugebauer et al., 2016). However, it should be highlighted that this method is at a very early development stage. These impact categories are only available at a conceptual level and there is no broadly accepted methodology to assess these impacts and AoPs. Nevertheless, including these aspects would be especially relevant for the assessment of aquaculture production at national level as done in this framework, because of the important contribution of aquaculture to many national economies. Despite the inclusion of a considerable number of economic factors in this study, the framework does not assess economic sustainability in a comprehensive way. The scenarios are built to ensure minimum macroeconomic viability, which is limited to the criteria and theories introduced in the model, but to assess comprehensively economic sustainability, an EcLCA should be included as well.

Therefore, when S-LCA and EcLCA will have reached a higher development stage and comport broadly accepted methodologies of impact quantification, the E-LCA of the current framework should be replaced by a full LCSA to improve the relevance of the framework. They would be based on the same scope, with the same system boundary

and using the same scenarios. The practitioner would need to select a set of social and economic impact categories to be included in the assessment. Then the requirements of the data collection would need to be adapted to cover economic and social aspects as well. In practice, including social and economic sustainability would require an extensively longer data collection phase, which has to be taken into account. Some information might be complicated to obtain, as the farmers might not know about them (e.g. contribution to economic development) and it would therefore become important to collaborate and share information with local authorities to obtain data on impacts that are more large-scale. Finally, common databases need to be adapted and supplemented to allow the inclusion of these impacts in a truly life cycle perspective.

6.3.3 Assessing absolute sustainability

In the current state of the framework, LCA is used to assess the environmental sustainability of the aquaculture sector. This methodology is a useful tool to compare environmental impacts of products and systems and to identify environmental trade-offs. However, it only allows determining which solution is the most environmentally friendly among a set of assessed ones, or to highlight potential burden shifting when prioritizing a solution over another. It is a tool for relative sustainability assessment, which focuses on the eco-efficiency of products and systems. Yet, as argued in section 5.3.3, eco-efficiency is not sufficient to ensure that society is evolving to a more sustainable state because it does not account for potential rebound effects produced by the increase of material affluence (i.e. an increase in demand - Hauschild, 2015). Thus, results from LCA indicators should not only be compared to each other, but to levels of impacts established as sustainable in a complementary approach (Bjørn et al., 2015). To that purpose, the concept of carrying capacity arises, defined as “the maximum sustained environmental interference a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert.” (Bjørn and Hauschild, 2015). It is only by remaining within the carrying capacity of the Earth system that society can meet absolute sustainability.

Therefore, it is needed to move towards assessments that can determine if a system is sustainable or unsustainable on an absolute scale. Some frameworks and methods of so-called absolute environmental sustainability assessments (AESA) have been proposed for assessing absolute sustainability. They use absolute environmental sustainability indicators (AESI), as opposed to the relative environmental sustainability indicators (RESI) used in the current LCA methodology (Bjørn et al., 2016). Therefore, so far, the developed AESIs are generally the combination of LCA indicators (i.e. RESI) and boundaries or thresholds corresponding to sustainability reference values based on the ecosystems' carrying capacity. This combination has been done in different ways, e.g. by introducing carrying capacity-based normalization factors in LCA as in Bjørn and Hauschild (2015) or by integrating the carrying capacities directly in the characterization factors like in Bjørn *et al.* (2016). Another difference between the methods proposed so far is the way the carrying capacity, or more generally the absolute boundaries, are

defined. The most common way has been to use the thresholds defined by the Planetary Boundary (PB) framework (see e.g. Ryberg *et al.*, 2016), introduced by Steffen *et al.* (2015) and which defines a safe operating space for humanity to occupy without risking to leave the stable Holocene state of the Earth's system. However, using the PB framework has some limitations, such as its limited coverage of anthropogenic impacts. The PB framework does not account for human health and resource impacts, which are two important AoP in the LCIA framework (Verones *et al.*, 2017). Additionally, some of the categories do not have quantified safe operating space yet (Steffen *et al.*, 2015). Therefore, AESAs would need to combine other methods with the PB framework to cover absolute sustainability comprehensively.

However, the introduction of boundaries in RESI does not alone allow preventing rebound effects, which is a requirement to reach absolute sustainability. This calls for rethinking the system boundaries as usually defined in LCA and the introduction of dynamic and extended system boundaries and/or FU to ensure that all the consequences of a change are included and considered. Methods to include systems dynamics in LCA have been proposed, like Kim, Kara and Hauschild (2017) who introduced a framework that accounts for consumer usage behavior linked to the introduction of new technologies as a dynamic FU. Likewise, Pinto, Sverdrup and Diemer (2019) combined system dynamics with LCA to assess the carbon footprint of the European steel industry within 2000-2200 in the context of circular economy. Accounting for all the consequences of the assessed function could improve the credibility and reliability of the scenarios, especially when having a prospective approach like in the framework developed in this PhD project. Additionally, it is the funding principle of consequential LCA, and it would therefore be especially relevant to combine LCA and system dynamics when the situation requires a consequential modelling as recommended in the ILCD handbook (EC, 2010), which is the case in this framework. This would be especially beneficial because the results of the framework are used as support for policy-making, and they would produce more comprehensive and reliable recommendations that help reaching absolute sustainability of food systems.

From a practical point of view, accounting for all the consequences of a new aquaculture growth policy would require having an overview of all systems and sectors that will be impacted by the change. With regard to food, substitutability between products is non-negligible and relies on very diverse criteria, such as price, availability, nutritional preferences and ethical/religious beliefs. For example, beef can be substituted by seafood to a certain extent, if seafood popularity increases due to e.g. lower prices, higher consumer interest for healthy diets or higher availability (as considered in section 5.3.3). Therefore, the change in the production of one food item (e.g. seafood) might have consequences on the production systems of other food items (e.g. beef), reflected by an increase/decrease in demand and thus in production. When addressing absolute sustainability, the system under study cannot be limited to one type of product (e.g. seafood), but should include the food industry as a whole. A similar phenomenon occurs

within countries. The globalization of food supply chains led to a high proportion of food products being imported/exported nowadays, with some countries/regions specializing their production around few items that are particularly compatible with their climatic and geographical situation. Thus, a change in production in one country might have consequences on the food system of other countries. Consequently, the assessment of just one country's production or consumption limits greatly the scope of a study and hence the potential conclusions and recommendations that can be drawn based on the results. Absolute sustainability therefore needs to be considered from a global perspective.

Therefore, combined with the arguments developed in the previous section in favor of the integration of economic and social sustainability (section 6.3.2), the LCA currently used in this framework should be transformed into a LCSA, and then treated in the light of absolute sustainability and system dynamics. This would allow determining if a policy is actually sustainable or not, not only if it is more sustainable than e.g. the absence of policy. This could lead to the conclusion that none of the assessed scenarios is sustainable, and that the policy cannot be implemented in a sustainable way, which would encourage policymakers to rethink their decisions based on potential improvements identified thanks to the framework. Another possible conclusion could be that all the selected scenarios are sustainable on an absolute scale, which means that other criteria can thus be considered in the decision process such as higher profits or consumers' preferences. However, it needs to be remembered that these approaches are still at an early stage of development and that no internationally accepted methodologies are available to be applied to practical cases today.

Overall, this calls for a modeling of the entire global food system, which would include all food products and their corresponding potential substitutability (usually expressed via elasticities) and all countries and their corresponding trade flows.

6.4 WHAT WOULD THE “PERFECT” FRAMEWORK LOOK LIKE TO ASSESS SEAFOOD POLICY IMPLICATIONS?

To conclude based on the improvement potentials identified in previous sections of this chapter, sustainability of future food policies should be assessed using an improved framework based on a dynamically interlinked and multimodal life cycle-based model:

- *Dynamically interlinked*: as it would include all food sectors and countries, linked using system dynamics to account for potential rebound and backfire effects due to economic or behavioral changes.
- *Multimodal*: as it would contain modules to quantify environmental, social and economic impacts in a life cycle perspective and with indicators accounting for

absolute boundaries, as well as a risk assessment module to assess the antimicrobial resistance impacts on human health.

With such a comprehensive approach, the implications of seafood but also food policies could be assessed in a much more reliable way, which would allow strong improvements regarding all dimensions of sustainability.

Ultimately, such framework would allow the global food system to reach true sustainability.

Chapter 7 CONCLUSIONS

RECOMMENDATIONS

&

7.1 PROJECT OUTCOMES & DOCTORAL ACHIEVEMENTS

The **research goal** of this PhD project, introduced in Chapter 2, was to find how to assess the current and prospective environmental sustainability of aquaculture growth policies (**RG**). To meet that goal, four research questions were defined and addressed throughout these 3 years of PhD.

- What are the main findings of past LCA studies assessing the environmental sustainability of aquaculture? (**RQ1**)

To address **RQ1**, I conducted a critical literature review of past LCA studies on aquaculture systems and analyzed their findings via the identification of common trends and tendencies. I presented these results in **Paper I**. My review allowed identifying a lack of studies on aquaculture in Asia, which is problematic due to the large majority of the global production originating from this continent. Feed production was highlighted as the dominant life cycle stage in the LCA of aquaculture systems, in agreement with other past reviews. The choice of technology type of the production system was recognized as crucial to the LCA results, which led to the need for a high level of differentiation in technology types when talking about environmental impacts of aquaculture systems. Finally, the use of LCA was recognized as a powerful tool for policy-makers and especially when used in large-scale studies.

- How environmental sustainability of aquaculture has been assessed in the past LCA studies in terms of methodological choices, and are there needs for improvement? (**RQ2**)

Based on the same body of literature, I analyzed the methodological choices of LCA practitioners in past LCA studies and identified several improvement potentials, which allowed addressing **RQ2**. Results were presented in **Papers IIa,b**. I found that, in past studies, the FU was often based on a live-weight mass of seafood at farm-gate, which is inconsistent with the consumer approach described by most of the studies. I recommended the use of an FU based on edible mass or portions, on nutritional characteristics (such as a mass of protein) or on complete diets to truly capture the functionality of the seafood system. The life cycle coverage as well as the impact coverage of past LCA studies were identified as generally too limited. I therefore recommended including all life cycle stages (incl. chemicals/infrastructures production and usage) and to assess a comprehensive set of impact categories (incl. toxicity impacts, resource scarcity ones and impacts specific to aquaculture such as NPPU). When it comes to

multifunctionality handling, past LCA studies were found to generally not respect the ISO standards recommendations rigorously and to hardly explain or argument their choices. I advocated more thorough compliance with the ISO standards accompanied by developed argumentation. Finally, I identified a lack of critical interpretation of the results, with few studies discussing the representativeness of their data or conducting uncertainty and sensitivity analyses. I called for more in-depth analyses of the limitations of LCA studies on aquaculture and for the systematic inclusion of qualitative uncertainty and quantitative sensitivity analyses.

- How can the evolution of national aquaculture sectors be modeled and foreseen when taking into account demand, supply (e.g. farming practices), trade and market mechanisms? (**RQ3**)

In **Paper III**, I adapted an existing economic demand-supply equilibrium model to a higher level of supply differentiation, and used it to anticipate the evolution of national seafood production sectors, accounting for demand, supply, trade and market mechanisms. I applied this model to create scenarios of aquaculture development in two countries, which contributed to addressing **RQ3** in a theoretical as well as a practical way. My first case study was the analysis of the “30-by-30” policy in Singapore during 2017-2040. I found that the business-as-usual scenario developed did not allow reaching the policies’ target, which reinforced the need for political actions. The target of the Singaporean government was reached in the two other scenarios developed, and a preference for one of them was identified based on lower imports and higher proportions of innovative technologies. The second case study was the analysis of the Norwegian aquaculture sector between 2017 and 2040 accounting for a willingness of the local government to diversify the production in terms of species and technologies. The model and results were displayed in **Paper V** and highlighted important difficulties to implement such change in the Norwegian production mix. None of the scenarios developed met the industry forecasts in terms of new species and the introduction of new technologies remained limited to a few recirculating aquaculture systems. This called for further investigations of the economic causes of such difficulties to identify potential leverages of change. Overall, the developed model proved to be operational and useful to foresee the evolution of aquaculture sectors in given countries.

- How can the environmental sustainability performance of the aquaculture sector at national scale be assessed in a foresight perspective? (**RQ4**)

To address **RQ4**, I developed an ex-ante framework and its associated methods and models to anticipate the environmental implications of aquaculture growth policies and give useful recommendations to policy-makers. I introduced and described the four steps of the framework that I designed in **Paper V**. The first step consisted of an in-depth description of the aquaculture sector. The second step relied on the economic model developed for assessing **RQ3** to create scenarios of aquaculture development. Step 3 was

a macro-scale LCA used to assess the environmental impacts of the obtained scenarios at national level, integrating recommendations from the critical review performed when addressing RQ1 and RQ2, and step 4 consisted of the interpretation of the results. An optional step O was developed and consisted of a micro-scale LCA that aimed at giving an overview of the environmental impacts of the different production systems in the assessed country in a foresight perspective. I then applied the complete framework on Singapore and Norway as a proof-of-concept for **RQ4** and discussed the results in **Paper V**. The optional step O was applied on the Singaporean case and its results were displayed and analyzed in **Paper IV**, in which the life cycle inventories developed were also disclosed transparently for future uptake by other LCA practitioners. The results of the two case studies led to the formulation of a set of recommendations to policy-makers and other aquaculture stakeholders regarding concrete ways of implementing the willing changes to their national aquaculture sector and how to reduce the environmental impacts of aquaculture production in these countries (see section 5.1 for Singapore and section 5.2 for Norway).

Overall, the framework developed allowed assessing the current and prospective environmental sustainability of aquaculture growth policies and proved to be adaptive to different case studies. It therefore answered the **research goal** of this PhD project.

7.2 RECOMMENDATIONS & FUTURE WORK

This PhD work led to the development of an unprecedented framework that allows anticipating the environmental implications of seafood policies in a present and future perspective. This constitutes a first step towards sustainability of global food systems. To go further, opportunities for future work and recommendations to future practitioners in all involved disciplines were identified throughout the whole thesis work. They are summarized in this section in the form of a table with target audience and cross-reference to the thesis' section each that recommendation was developed.

Table 14: Summary of recommendations highlighted in this PhD project with the corresponding target audience and cross-reference in the thesis.

Target audience	Recommendations	Cross-reference
<i>LCA practitioners in aquaculture</i>	Conduct LCA studies on regions, species and technologies that have received low attention so far.	3.2
	Conduct LCA studies on large-scale systems and/or with a prospective perspective.	3.2
	Improve the LCA application on aquaculture systems by choosing a functional unit that reflects the goal of the study, having a large life cycle coverage and a large impact coverage, following the ISO standards for multifunctionality handling and critically discussing the results and data.	3.3
	Improve data and methodological transparency of LCA studies on aquaculture.	3.3
	Develop a user-friendly version of LCA studies on aquaculture, where LCIs would be created automatically based on the systems characteristics communicated by an external user.	6.1
<i>LCA practitioners in aquaculture & biologists</i>	Investigate how to reduce environmental impacts of feed production and usage while accounting for biological needs and characteristics of the different seafood species.	3.2.2
<i>LCI developers and common databases</i>	Develop LCIs on aquaculture production differentiated by technology, species and region of production.	3.3.5
	Adapt common databases to social and economic impact categories to make life cycle sustainability assessment usable in practice.	6.3.2
<i>LCA method developers & ecosystem specialists</i>	Develop new impact pathways for missing impacts linked to aquaculture such as escapes and antimicrobial resistance.	3.3.4
<i>Food/resources economists</i>	Conduct economic studies on food/seafood in countries/regions that have been neglected so far, for a better understanding of consumers' behavior and for the production of adapted demand/supply/expenditure elasticities.	6.1
	Make demand/supply equilibrium models that are more user-friendly.	6.1
<i>National and industrial statistic entities</i>	Improve the communication of national, regional and industrial statistics/data regarding aquaculture production (quantities and value) with a high level of species differentiation.	6.1
	Introduce regulations to encourage the production of marine fishes in sea cages, offshore systems and	5.1.3

<i>National policy-makers in Singapore</i>	recirculating aquaculture systems, due to their environmental benefits and low land requirements.	
	Get inspired by the production mix described in the second scenario, i.e. with an important penetration of innovative technologies.	5.1.7
<i>National policy-makers in Norway</i>	Require macroeconomic studies to identify the source of the failure of aquaculture diversification.	5.2.3
	Encourage integrated multi-trophic aquaculture and recirculating aquaculture systems for their environmental benefits.	5.2.5
	Encourage further technology optimization regarding the production of white fishes in sea cages due to their current environmental burden.	5.2.5
<i>National policy-makers (both)</i>	Encourage the use of trimmings in the manufacturing of fishmeal and fish oil.	5.1.6 5.2.5
	Encourage further technology optimization regarding production of insect- and algae-based feed due to their current environmental burden.	5.1.6 5.2.5
<i>Aquaculture producers</i>	Prioritize the use of fishmeal and fish oil from a high proportion of trimmings to reduce the pressure on wild stocks.	5.3.1
	Use food industry by-products when possible and fit the biological requirements of the fishes to reduce the pressure on wild stocks.	5.1.6
	Collect and sell/give nutrients' sludge (when closed system) to neighboring agriculture farms as natural fertilizer to reduce eutrophication impacts.	5.1.6
	Collaborate with biologists to design optimized feed diets that reduce the feed conversion ratio while meeting all biological requirements of the seafood.	5.3.1 3.2.2
	Implement a module for environmental impacts in the economic model.	6.1
<i>Future practitioners of the developed framework</i>	Develop the framework to include absolute sustainability, life cycle sustainability assessment and antimicrobial resistance risk assessment.	6.3
	Make the adapted framework dynamic and containing the entire food sector globally, to make it truly consequential.	6.3.3

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GLOSSARY

Concept	Definition	
Absolute sustainability	Sustainability quantified on an absolute scale, usually based to a defined boundary corresponding to the maximum carrying capacity of the Earth system combined with an operating space attributed to the assessed function. Not compared to other products or systems.	⁰
Allocation	Dividing the inputs and outputs of the multifunctional process or system between the different products or functions.	¹
Antimicrobial resistance	Ability of a microorganism (like bacteria, viruses, and some parasites) to stop an antimicrobial (such as antibiotics, antivirals and antimalarials) from working against it. As a result, standard treatments become ineffective, infections persist and may spread to others.	²
Aquaculture production mix	Repartition of the aquaculture production of a country among the different production categories within the total production. Reflects the aquaculture landscape of the country at a specific moment in time.	⁰
Aquafeed	Feed used in aquaculture.	⁰
Attributional modelling	Quantification of the environmental impacts that can be attributed to the product system based on a mapping of the emission and resource flows that accompany the product as it moves through its life cycle, applying representative average data for all processes involved in the life cycle in a book keeping approach	³
Carrying capacity	The maximum sustained environmental interference a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert.	⁴
Climate change short term	Effect of greenhouse gas accumulation in the atmosphere that leads to positive radiative forcing, which may cause different climate effects such as increasing temperature or extreme weather events. Based on Global Warming Potential for a 100-year time horizon	⁵
Climate change, long term	Effect of greenhouse gas accumulation in the atmosphere that leads to positive radiative forcing, which may cause different climate effects such as increasing temperature or extreme weather events. Based on Global Temperature Potential for a 100-year time horizon	⁵
Consequential modelling	The consequential perspective is concerned with the potential consequences of the decision based on the results of the LCA, and involves modelling of the broader economic system that the decision affects	³
Eco-effectiveness	Concept that corresponds to the optimization/decrease of the inputs as well as unwilling outputs (i.e. emissions and wastes) compared to the desired output (i.e. product). In other words, decrease of the environmental impacts per unit produced.	⁰
Eco-efficiency	Concept that corresponds to the optimization/decrease of the environmental impacts overall. In other words, decrease of the total environmental impacts corresponding to a function accounting for external factors, e.g. rebound effects, not only per unit produced.	⁰
Ecosystems	Damages on the intrinsic value of natural ecosystems, through potentially disappeared fraction of species	⁵
Endpoint	The category endpoint is an attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern (ISO 14040). Hence, endpoint method (or damage	⁶

	approach)/model is a characterization method/model that provides indicators at the level of Areas of Protection (natural environment's ecosystems, human health, resource availability) or at a level close to the Areas of Protection level.	
Feed conversion ratio	Mass of aquafeed needed per unit of live-weight mass gained by the specimen during growth	⁰
Fossil and nuclear energy use	Primary energy content use from fossil fuels and nuclear sources	⁵
Freshwater acidification	Negative effects of increasing acidification of the freshwater that may change the pH of the compartment and impact biodiversity	⁵
Freshwater ecotoxicity	Negative effect of chemical substances emitted in freshwater on local biodiversity	⁵
Freshwater eutrophication	Negative effect of increasing nutrient concentration in the freshwater that may lead to decreased levels of oxygen and therefore impact biodiversity	⁵
Functional unit	A quantitative description of the function or service for which the assessment is performed, and the basis of determining the reference flow of product that scales the data collection in the next LCA phase, the inventory analysis.	⁷
Human health	Damages on the intrinsic value of human health, accounting for both mortality and morbidity	⁵
Human toxicity cancer	Negative effect of chemical substances emitted in freshwater, terrestrial and marine ecosystems, which might impact human population through different pathways (e.g. inhalation of air, ingestion of food and water), and may cause cancers	⁵
Human toxicity non cancer	Negative effect of chemical substances emitted in freshwater, terrestrial and marine ecosystems, which might impact human population through different pathways (e.g. inhalation of air, ingestion of food and water), and may cause multiple diseases non-cancerous	⁵
Impact category	Class representing environmental issue of concern, e.g. Climate change, Acidification, Ecotoxicity etc.	⁸
Ionizing radiations	Negative effect due to release of radioactive material to the environment	⁵
Land occupation, biodiversity	Impacts on land due to anthropogenic occupation of land	⁵
Land transformation, biodiversity	Impacts on land due to anthropogenic transformation of land from its natural state	⁵
Life cycle assessment	ISO-standardized methodology to quantify environmental impacts of products, services or systems over their whole life cycle and for multiple environmental impact categories.	⁰
Life cycle impact assessment	The third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study.	⁶
Life cycle inventory	The second phase of life cycle assessment, involving the collection and inventory of all inputs and outputs for a given product system throughout its life cycle. The outcome of a life cycle inventory is a catalogue of the flows crossing the system boundary and provides the starting point for life cycle impact assessment.	⁸
Marine eutrophication	Negative effect of increasing nutrient concentration in the ocean that may lead to decreased levels of oxygen and therefore impact biodiversity	⁵

Midpoint	The midpoint method is a characterization method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level.	6
Mineral resource use	Fraction of material needed by future users that are not able to adapt to a full dissipation of the easily available stock	5
Monoculture	Farming of a single species.	0
Multifunctionality handling	A process is multifunctional when it provides more than one function, meaning that it either delivers more than one product output and/or provides more than one service. As soon as a by-product arises from a multifunctional process, it is economic common sense to try to utilize it, often in a different context from the product system being analyzed in the LCA. This means that the process becomes part of another product system as well, and that the environmental impacts from the process can no longer be fully ascribed to the product system studied, and some impacts need to be attributed to it.	9
Net primary production use	Biotic resource that is not available for other systems anymore	10
Ozone layer depletion	Negative effect due to the destruction of the ozone layer from human activity	5
Particulate matter formation	Negative effect on human health due to inhalation of fine particulate matter (PM2.5), i.e. particles with diameter less than 2.5 μm	5
Photochemical oxidant formation	Negative effect of increasing ozone concentration in the atmosphere which can lead to increased frequency and severity of respiratory diseases	5
Planetary boundaries framework	The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come.	11
Polyculture	The simultaneous farming of several seafood species.	0
Production category	Ensemble of production systems characterized by the same species group and the same technology type. Existing or prospective, as identified in step 1 of the framework.	0
Risk assessment	Scientific evaluation of known or potential adverse health effects resulting from human exposure to foodborne hazards	12
Species group	Grouping of species that require similar farming systems to grow (and thus inputs, outputs and emissions), that are therefore meaningful to gather when assessing the environmental impacts.	0
System dynamics	Methodology for studying complex nonlinear behavior within systems, often used for simulating new potential behaviors by adding, removing or changing variables, triggers and delays	13
System expansion	Expanding the multifunctional process with the most likely alternative way of providing its secondary function.	1
Technological factor	Proportional change of netput n due to technological progress or policy shift at year y compared to the starting year of the model	14
Technology type	Technologies with similar farming processes (and thus inputs, outputs and emissions), that are therefore meaningful to gather when assessing the environmental impacts.	0
Terrestrial acidification	Negative effects of increasing acidification of the soil that may change the pH of the compartment and impact biodiversity	5

Trimming	All unwanted or inedible parts of the fish (i.e. sinews, skin, fat etc.). Output in the food industry that cannot be used for human consumption	⁰
Water scarcity	Remaining water available per area after human and aquatic ecosystem demand has been met, relative to the world average	⁵

⁰: Own definition.

¹: ISO, 2006. ISO 14044:2006 - Environmental management – Life cycle assessment – Requirements and guidelines. Geneva, Switzerland.

²: WHO, 2019. Antimicrobial resistance. [www document] URL <https://www.who.int/antimicrobial-resistance/en/> (accessed on 03.02.2020)

³: Bjørn, A., Owsianiak, M., Molin, C. and Hauschild, M.Z., 2018. LCA History (Chapter 3). In: Hauschild, M.Z., Rosenbaum, R., Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice. Springer, Dordrecht, NL, pp. 167–270.

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⁶: EC, 2010. International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance, First Edit. ed. Publications Office of the European Union, Luxembourg.

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⁸: ISO, 2006. ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. Geneva, Switzerland.

⁹: Bjørn, A., Owsianiak, M., Laurent, A., Olsen, S.I., Corona, A. and Hauschild, M.Z., 2018. Scope definition (Chapter 8). In: Hauschild, M.Z., Rosenbaum, R., Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice. Springer, Dordrecht, NL, pp. 167–270.

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¹¹: Stockholm Resilience Center, 2019. Planetary Boundaries. [www document] URL <https://www.stockholmresilience.org/research/planetary-boundaries.html> (accessed on 03.02.2020)

¹²: WHO, 2019. Risk assessment.. [www document] URL <https://www.who.int/foodsafety/micro/riskassessment/en/> (accessed on 03.02.2020)

¹³: Pinto, J.T.M., Sverdrup, H.U., Diemer, A., 2019. Integrating life cycle analysis into system dynamics: the case of steel in Europe. Environ. Syst. Res. 8.

¹⁴: 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.

APPENDIX 1: FARMERS' IN-DEPTH INTERVIEW GUIDE

This questionnaire was developed in collaboration with Dr. Chengcheng Hu, Mr. Glendon Ong and Prof. Jørgen Schlundt.

Can you tell us about your farm?

1. **Characteristics:** Farm size (m²), herd size, fish and seafood species, type of aquaculture (mono/polyculture/integrated multi-trophic aquaculture), land-based/coastal farm?
2. **Land use:** on which type of land is the farm built (forest, mangrove, coastal area)?
3. **Technology:** What kind of technology have you applied to your farm (e.g. RAS system)? What kind of infrastructure and equipment have you used for the farm setup?
4. **Production:** How much does your farm produce per year (in kg or other units per year)? Is it possible that fish escape from your farm, into the surrounding environment? If yes, do you have an idea of how many fish escape per year?

Can you tell us about your production process inputs and outputs?

5. **Fry:** Where and how do you get the fry? Do you have hatchery system in the farm? Quality of the fry/Survival of the fry
6. **Feed:** What type of feed do you use in your farm? Do you use different feed for the different life stages (fry, larvae, on-growing)? What is the composition of the feed used? Do you have estimates of how much feed you use per weight gain at each step of the life of the fish (sometimes expressed as FCR - feed conversion ratio)?
7. **Energy input:** How much water and electricity do you spend per month/year? Any other energy input (e.g. fuels)? Does the culture system consume oxygen?
8. **Chemicals input:** Do you use chemicals (e.g. disinfectants, anti-fouling agents, fertilizers) in the farm? If yes, what kind of chemicals and in which quantity per quantity of fish produced/per months? Do you use manure from the production of other animals – if yes, in which quantity per quantity of fish produced?
9. **Waste and treatment:** Is the farm equipped with wastewater treatment? If yes, which ones, and how efficient are they? How and where do you discharge the wastewater/ the treated water?
10. **Post-farming process:** Do you have any post-farming processes in your farm (slaughtering, gutting, filleting, cooking, and packaging)? If yes, which ones exactly, and do you process your whole production? Do you sell your own products directly to consumers? If not, to whom do you sell your products to

(local resellers/ large reselling companies/ processing companies)? Do you have knowledge about what happens to your product after it leaves your farm?

APPENDIX 2: STANDARD DATA COLLECTION TABLE

Category	Information	Unit/details	Data
General information	Date of the interview		
	Farm n#		
	Farm name		
	Geographical location of the farm		
Background	Farm size	<i>On land (m²)</i>	
		<i>At sea (m²)</i>	
	Production	<i>Tons/yr</i>	
	Species (weight when sold)	<i>Name (kg)</i>	
	Mono/polyculture		
	Stock density	<i>p/m³</i>	
	Offshore/Onshore		
	Water type	<i>Freshwater or seawater?</i>	
	Land use	<i>Natural state of the land</i>	
	Technologies and equipment (Cages? Platform? Nets? Ponds? Pipes? Devices? Boats? etc)	<i>Main</i>	
		<i>Details (amount and size of each item, composition, technology level, etc)</i>	
Fry/Fingerlings	Escapes	<i>Yes/No</i>	
		<i>p/yr</i>	
	Origin		
	Weight	<i>g</i>	
Feed	Survival rate	<i>%</i>	
	Remark		
	Ingredients	<i>Name + origin</i>	
	Composition	<i>% for each ingredient</i>	
	FCR	<i>Unitless</i>	
Water	Price	<i>\$/yr</i>	
	Remarks		
	Freshwater	<i>m³/yr</i>	
	Sea water	<i>m³/yr</i>	
	Bill (in case consumption unknown)	<i>\$/yr</i>	
Energy	Remarks		
	Electricity consumption from the grid	<i>Yes/No</i> <i>If yes, kWh/yr</i>	
	Bill (in case consumption unknown)	<i>\$/yr</i>	
	Fuel for boats	<i>Yes/No</i> <i>If yes, Kg/yr</i>	
Consumables	Other energy use	<i>Type(s)</i> <i>Kg/yr</i>	
	Disinfectants	<i>Type(s)</i>	
	Amount	<i>kg/yr</i>	
	Fertilizers	<i>Type(s)</i>	
	Amount	<i>kg/yr</i>	

Appendix 2: Standard data collection table

	Antibiotics	Type(s)	
	Amount	kg/yr	
	Oxygenation of the water	Yes/No If yes, kg/yr	
	Amount	kg/yr	
	Other?		
Waste & Wastewater treatment	Wastewater	On-site treatment? Released in nature? General wastewater system?	
	Amount	m ³ /year	
	Other waste	Type? Treatment? kg/yr	
Post-farming	On-site post-farming	Filleting? Gutting? Other?	
	Buyers	Domestic/foreign	

PAPER I

Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development

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Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development

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Abstract

The aquaculture sector is anticipated to be a keystone in food production systems in the coming decades. However, it is associated with potentially important environmental damages caused by its contribution to eutrophication or climate change, for example. To comprehensively quantify those impacts, life cycle assessment (LCA) studies have been conducted on several seafood farming systems for the past 15 years. But, what major findings and common trends can we draw from this pool of studies? What can we learn to provide recommendations to decision and policymakers in the aquaculture sector? To address these questions, we performed a critical review of 65 LCA studies of aquaculture systems from the open literature. We conducted quantitative analyses to explore which impacts can be identified as dominating and to compare different types of aquaculture systems. Our results evidenced that the feed production is a key driver for climate change, acidification, cumulative energy use and net primary production use, while the farming process is a key driver for eutrophication. We also found that different aquaculture systems and technology components may exert considerably different environmental impacts. Based on identified patterns and comparisons, we therefore provided specific recommendations to aquaculture stakeholders for future policy and system development. Overall, the analysis of existing studies demonstrates that important insights can be gained by applying LCA to aquaculture systems, and, to move towards an environmentally sustainable aquaculture sector, we recommend its systematic use in the design of new aquaculture systems or policies, and/or in the evaluation and optimization of existing ones.

Key words: aquaculture, aquafeed, environmental impacts, food production, life cycle assessment, sustainability.

Introduction

Aquaculture has been identified as a promising alternative to fisheries to tackle the growing food security issue while avoiding depletion of wild fish stocks (World Bank 2013). This sector has been growing dramatically for decades, from a global production of less than 10 million tons in 1985 to 73.8 million tons in 2014 (FAO 2016). Even though seafood farming is often claimed to be sustainable (e.g. Tlustý & Thorsen 2016), it is associated with multiple potential environmental impacts such as eutrophication of aquatic ecosystems, intensive use of land and water,

ecotoxicity in local ecosystems through the use of chemicals and introduction of nonindigenous species (Naylor *et al.* 2000; Diana 2009; Ottinger *et al.* 2016). It is thus highly relevant to assess current aquaculture practices and identify the aquaculture production systems that are the most environmentally sustainable.

Environmental sustainability has been defined as the ‘maintenance of natural capital’, also known as the input/output rules that could be summarized as followed: the waste emissions caused by a project or action should not exceed the capacity of the local environment (output rule) and the natural resources should be

harvested at a rate that allow regeneration (input rule) (Goodland 1995; Goodland & Daly 1996). A tool commonly used to assess the environmental sustainability of food production systems is life cycle assessment (LCA), which has already proven its value in the path to more sustainable food (Andersson 2000; Mungkung & Gheewala 2007; Ziegler *et al.* 2016). LCA is an ISO-standardized methodology, which quantifies the impacts on ecosystems, human health and natural resources stemming from products and systems throughout their entire life cycle, that is from the extraction of the raw materials through their production and use or operation up to their final decommissioning and disposal (ISO 2006; EC 2010). This tool can be used to assess multiple impact categories, such as climate change, eutrophication to aquatic environments (termed ‘aquatic eutrophication’ hereafter) or toxicity of chemical releases impacting human health (termed ‘human toxicity’ hereafter) and ecosystems (termed ‘ecotoxicity’ hereafter). LCA can be used to support decision-making in aquaculture by identifying the hotspots of a system to reduce their environmental impacts or by comparing several alternative systems to determine which one has the lowest environmental impacts among analysed alternatives. This can be done at micro-level (e.g. focus on a specific process, such as feed production), meso-level (like assessing an entire farm) or macro-level (like assessing the aquaculture sector or an entire country).

Several LCA studies have been performed on aquaculture systems, as illustrated in Figure 1. Altogether, they form a considerable set of assessments, which should be comprehensively investigated to identify trends and common patterns in their findings as well as evaluate how they adapt and apply LCA to aquaculture systems and products (Ziegler *et al.* 2016). Although relevant, such analyses have not been reported in the literature since 2013. Most existing reviews of the application of LCAs to aquaculture systems have had a narrow scoping, for example focusing on a specific impact category or country (Nijdam *et al.* 2012; Pahri *et al.* 2015; Soliman & Yacout 2015; Cashion *et al.* 2016) or, when of a broader scope, have only considered a limited number of LCA studies, and/or only studies published until 2013 (Henriksson *et al.* 2012; Parker 2012; Aubin 2013; Cao *et al.* 2013; Clark & Tilman 2017). A large pool of studies – and associated findings – could therefore not be included in these reviews (see Fig. 1).

This study aimed to bridge this knowledge gap by performing a comprehensive critical review of the findings and lessons learned from LCA studies of aquaculture systems, as currently available in the literature. The objectives of the study were to (i) provide a comprehensive mapping of all the LCA studies published up to mid-2017 that included aquaculture systems producing food and aquaculture feed;

Figure 1 Temporal evolution in the total number of life cycle assessment studies of aquaculture systems and the ones included in general reviews published until mid-2017. (■) All studies found and considered in current study (total of 65 studies) and (□) studies reviewed in previously-published general critical reviews (total of 23 studies).

(ii) conduct a statistical analysis of the LCA results to identify impact patterns and characterize environmental impacts for aquaculture systems; (iii) explore the influences and contributions of the different components of the life cycle of aquaculture systems; (iv) perform comparative analyses of the aquaculture systems, accounting for differences in intensity, technology, feed conversion ratio (FCR) and types of farmed species; and (v) discuss the relevance of LCA in a policy- and decision-making context within the field of aquaculture.

Review methodology

Scoping of the review

We included all LCA studies of one or several aquaculture systems or aquafeed production systems. Studies limited to reporting of emission inventories, social-LCA studies and pure economic assessments were dismissed. The focus being on food production, aquaculture systems designed to produce biogas, biofuels or bioactive compounds was also excluded. Fisheries, despite mainly producing food for human consumption, constitute an area of research in their own right and present other environmental problematics than aquaculture (see recent review by Ziegler *et al.* 2016); they were thus excluded from the scope of the study. However, studies conducting comparisons between fisheries and fish farms were included, although only the results concerning the fish farming systems were encompassed in the review. Finally, only studies including assessments of at least two environmental impact categories were included. An

exception was made for Cashion *et al.* (2016), who considered only net primary production use (NPPU), an impact category used specifically in food production. Environmental impact categories of relevance for aquaculture systems could be climate change, aquatic eutrophication, acidification, freshwater ecotoxicity or marine ecotoxicity (Mungkung *et al.* 2006; Henriksson *et al.* 2012). Assessments of climate change or carbon footprints alone were therefore excluded.

Identification of the studies

We only included studies published in scientific journals, conference proceedings and independent research centre reports that were peer-reviewed and written in English. The identification of the studies was performed using Web of Science database (<http://webofknowledge.com>) and Google Scholar search engine (<https://scholar.google.dk/>) with the search words 'Life cycle assessment' + 'aquaculture', 'Life cycle analysis' + 'aquaculture', 'LCA' + 'aquaculture', 'Life cycle assessment' + 'aquafeed' and 'Life cycle assessment' + 'aquaculture' + 'feed'. Additionally, the cited and citing articles in the five previously published general critical reviews (Henriksson *et al.* 2012; Parker 2012; Aubin 2013; Cao *et al.* 2013; Clark & Tilman 2017) were crosschecked for additional studies.

Review criteria

The retrieved studies were analysed and the cases they assessed were extracted. A case was defined as a system with a specific set of characteristics that has been subject to an LCA and thus assessed with regard to its contribution to some environmental impacts. For each case, the methodological characteristics of the assessment (such as the specified functional output as defined by the functional unit or the applied life cycle impact assessment methodology), the general characteristics of the studied aquaculture system (e.g. type of culture, cultured species or geographical location) and the lessons learned from the study were extracted and categorized. The current review focuses on the two latter aspects, as an analysis of the LCA methodological aspects of the studies is the focus of another paper (Bohnes & Laurent 2018). Nonetheless, some central methodological aspects of importance for the analysis of the findings (like the functional unit) are also addressed here.

Similarities and differences between the cases assessed within a given study are determined from the general characteristics of the aquaculture systems. The main criteria used to map the cases are the culture intensity (intensive, semi-intensive or extensive), the culture diversity (monoculture or polyculture), the culture environment (freshwater culture or coastal culture; FAO 2017a), the species cultivated and the technologies used. The system size, despite being relevant

for our analysis, was not considered as a criterion because of a lack of information available in the LCA studies reviewed. A summary of criteria with detailed definitions is available in Table S1. The main findings of the studies were extracted and linked to the characteristics of each case to highlight potential patterns and allow for themed analyses (see Section Analysis of the findings).

Analysis of the findings

The results were analysed in two distinctive ways. First, a statistical analysis was conducted on the LCA results compiled from all retrieved cases, aiming to draw an extended picture of all studies when taken together. The findings and conclusions within each study were then gathered by theme and analysed to find overall patterns and trends.

General overview and statistical analysis

The impact indicator scores for four commonly assessed LCA impact categories, that is climate change, aquatic eutrophication, acidification and cumulative energy demand, and two aquaculture-related impact categories, that is water dependence (water input relative to fish biomass production; Aubin *et al.* 2009) and net primary production use (NPPU), have been extracted from the studies for each case. This selection was motivated by the data availability of the indicators in the total pool of LCA studies.

The functional unit (FU), which quantifies the service or function that the system provides, was retrieved and used to harmonize the results and make them relatively comparable (see below). The FUs could be divided into two categories: (i) functional units defined as production of mass-based 'live-weight product' (e.g. '1 kg of live-weight fish at farm gate') and (ii) functional units defined as supply of mass-based 'edible product' (e.g. '1 kg of fish fillet' or '1 kg of edible mussels'). The usable fractions (i.e. the edible part of the seafood) used in the latter studies were retrieved to bring all results to a common basis of 'live-weight FU'. We chose to harmonize the cases based on the live-weight product quantity because of the large amount of studies using this type of functional unit (78%). The relevance of such a functional unit is discussed in a follow-up paper, focusing on methodological aspects (Bohnes & Laurent 2018). It is worth noting that no further harmonization of the results was performed (e.g. consideration and/or alignment of system boundaries or LCI modelling framework), and the remaining differences must therefore be regarded as a source of uncertainties.

The harmonized results were subject to multiple regression analyses to explore the influence of seven system characteristics: culture intensity, culture diversity, culture environment, specie(s) cultivated, technologies used, location of the system (i.e. continent) and feed conversion ratio

(FCR). The analysis was performed using the software R v3.4 (R Core Team 2013) and the statistical significance was assessed using *F*-tests once the variable tested was checked to be normally distributed.

Contribution assessment and comparative analysis

A semi-quantitative analysis was additionally conducted to identify and highlight potential trends in the main conclusions across the analysed studies. The degree of consensus around the main findings was calculated as the ratio between the number of studies explicitly concluding on a finding and the total number of studies that were eligible to that conclusion. For example, cases assessing aquaculture systems producing nonfed species such as mussels are not eligible to conclusions regarding feed production or FCR as they do not use aquafeed. Furthermore, to compare the performances of different aquaculture system options, differences in impact scores between cases within one study were averaged and compared. Such an approach enables a more meaningful comparison between aquaculture systems because it avoids some of the methodological differences and discrepancies that may be present between different studies.

Overview of assessed cases and statistical analysis

Overview of LCA studies in a global perspective

In the literature collection, a total of 65 peer-reviewed studies were retrieved, containing a total of 217 cases, among which 179 were aquaculture systems (see Table S2) and 38 were aquafeed systems (see Table S3).

The overview of the studies reveals an important discrepancy between the geographical distribution of the systems assessed in the LCA studies and the global distribution of the production of farmed fish – see Figure 2a. While Asia represents approximately 90% of the global aquaculture production, only 24% of the LCA studies assessed an aquaculture system located on this continent. On the other hand, Europe is greatly overrepresented among the LCA studies, with approximately half of them, while it only accounts for 3% of the global production. This suggests that concerns about environmental sustainability and the use of LCA to assess it are limited in Asia, and it therefore calls for more LCA studies performed on aquaculture systems in this region.

A similar discrepancy can be observed for the type of species covered in the studies (Fig. 2b). Diadromous fish thus only represent 7% of the global aquaculture production while they are the focus of 42% of the studies. In contrast, freshwater fish, which represent almost 60% of the production, only account for a quarter of the studies. One explanation may be that salmon, a diadromous fish,

is currently the most consumed fish from aquaculture in Europe (EUMOFA 2015), where most LCA studies have been performed until now, which is likely why it has been investigated in many LCA studies – see Figure 2a (EUMOFA 2015).

Overall environmental performances

Figure 3 presents the impact scores harmonized to 1 ton of live-weight seafood output for six selected environmental impact categories. While the range between the first and the third quartile is limited for some impact categories, like 2072–4658 kgCO₂-eq/t-live-weight for climate change and 32–74 kgPO₄³⁻-eq/t-live-weight for aquatic eutrophication, large variations are witnessed between the cases with the lowest and the highest scores, spanning over several orders of magnitude regardless of the considered impact category. Such discrepancies are likely to stem from different methodological choices in the scoping of the assessments. This misalignment across the scope of the studies has been recognized to significantly hamper the comparability of the studies (Brandão *et al.* 2012). Very scarce have been the attempts at performing comprehensive meta-analyses of LCA studies, where some of the key assumptions and methodological choices have been reworked and harmonized, like for electricity generation technologies in 2012 (see Special Issue S1 in Volume 16 of *J. Ind. Ecol.*; Brandão *et al.* 2012; Heath & Mann 2012; Lifset 2012). With respect to aquaculture systems, the generally incomplete

Figure 2 Differences in (a) geographical (■ Africa; ■ Asia; ■ Europe; ■ America and ■ Oceania) and (b) species distributions between life cycle assessment studies and actual production of farmed seafood worldwide in 2015 (data from global production extracted from FAO 2017b). ■ Marine fishes; ■ Freshwater fishes; ■ Diadromous fishes; ■ Crustaceans and ■ Molluscs.

Figure 3 Impact per ton of live-weight seafood product for six selected impact categories (from 140 cases of 179, communicating usable fraction and quantitative impact results). Midline is the median; box plots indicate the first and third quartile; whiskers indicate the maximum and the minimum values retrieved.

documentation of key assumptions and methods in LCA studies precluded the possibility for such a comprehensive meta-analysis. Nevertheless, with the alignment of the functional units to bring all impact scores on a common scale (see Section General overview and statistical analysis), the obtained results are believed to give useful, albeit crude, indications of the range of impact indicator scores for aquaculture impacts.

Across the studies, an average of 4.4 tons CO₂-eq per ton of seafood produced is found for climate change. Given that the average global consumption of fish per year is approximately 20 kg per capita and that half of it is farmed fish (FAO 2016), it corresponds to an impact of 44 kg CO₂-eq per year per capita for farmed fish consumption alone, or approximately 0.6% of the annual climate change impacts of an average person in the world (Laurent *et al.* 2011). Similar calculations result in fish consumption taking up to 3.8% and 1% of the annual per capita impacts for aquatic eutrophication and acidification, respectively (Sleeswijk *et al.* 2008). When compared to the background environmental loads from society, the contribution from aquaculture systems to aquatic eutrophication is thus

higher than contributions to climate change and acidification.

Some cases were found to have negative impact scores. Negative scores may arise in cases where the multifunctionality of some processes (such as production of multiple species in the same pond) is handled by ‘system expansion’, where the not required function is substituting an alternative way of providing it, and the aquaculture system is credited with the impact thus avoided, which may result in a negative overall sum of impacts (EC 2010).

Influential system parameters

To assess which factors have an influence on the results, a multiple linear regression was applied to the results of Figure 3 (excluding the country and sector-level assessments), with evaluation of several parameters – see Table 1. Although uncertainties exist in the results due to, among others, different methodological choices in the studies (see Section Analysis of the findings), a number of general patterns can be identified, with very different influences exerted by the tested parameters. The farming technology

thus appears to be influential for all considered impact categories but acidification, and the FCR seems influential for climate change, aquatic eutrophication and cumulative energy demand. They show that encouraging the development of some technologies over others could improve the global environmental impacts of aquaculture (see further details on this topic in Section Technology types). The importance of FCR, and hence of aquafeed in general, has already been highlighted by numerous LCA practitioners, and Aubin (2013) already concluded from his literature review that the feed production was the major environmental impact source. Aquafeed of carnivorous fish in intensive systems (such as Atlantic salmon) is mainly composed of products from fisheries (FAO 2018), therefore improvement of fishing techniques will also help reduce the aquaculture impacts caused by the feed consumption. The importance of feed and how to improve its environmental impacts is further developed in Sections Feed production and influence of FCR and Intensity of aquaculture systems.

In contrast to species type and FCR, the culture type shows little influence on the impacts (only influential on aquatic eutrophication results). This suggests that monoculture and polyculture systems may not have significantly

different impacts. This may be explained by the large variety of each system, which can use state-of-the-art technologies just as well as traditional farming methods (see Section Monoculture versus polyculture). With regard to the culture intensity, influence on the results was found only for acidification (see Table 1), hence environmental preference to either type of aquaculture systems can hardly be given. This may be explained by the high productivity of intensive systems that manage to balance the higher input of energy and resources. It might also be caused by the existence of an interaction between the parameter 'intensity' with other parameters included in the model, such as 'technology'.

The results displayed in Table 1 can provide some potential clues for improving the environmental impacts of aquaculture systems. For example, it is observed that all impacts but NPPU and water dependence seem to increase when the FCR increase. Reduction of the FCR should thus be regarded as a priority, for example by changing the aquafeed diet (see further details in Section Improving feed production). Likewise, recirculating aquaculture systems (RAS) seem to entail an increase in climate change impact and energy demand (compared to other technologies), due

Table 1 Overview of the results of the multiple regression applied on six impact categories and considering seven explanatory variables

Impact category $N_{\max} = 89^{\dagger}$	Explanatory variables						
	FCR	Culture intensity	Culture type	Technology	Species	Culture environment	Continent
Climate change	*** (+)	N.S.	N.S.	*** RAS (+) Cage/Nets (–)	N.S.	** Freshwater (–)	N.S.
Aquatic eutrophication	*** (+)	N.S.	* Polyculture (+)	*** FTS (+) RAS (+)	N.S.	*** Freshwater (–)	*** North America (–)
Acidification	N.S.	*** Extensive (+)	N.S.	N.S.	* Diadromous (–)	N.S.	N.S.
Cumulative energy demand	* (+)	N.S.	N.S.	*** RAS (+) Cages/Nets (–)	*** Multiple (+)	N.S.	N.S.
Water dependence	N.S.	N.S.	N.S.	* FTS (+) Cages/Nets (–) RAS (–)	N.S.	N.S.	N.S.
NPPU	N.S.	N.S.	N.S.	** Cages/Nets (+)	*** Crustacea N.S. (+)	* Freshwater (+)	*** Asia (–) South America (–)

Statistical significance (*F*-test) is reflected as follows: ***corresponds to *P*-value <0.001, ** to *P*-value <0.01, * to a *P*-value <0.05, 'N.S.' to *P*-value >0.05 (not significant).

[†]Among the 179 cases of aquaculture systems that were found in total, some did not communicate the results quantitatively or did not communicate the usable fraction or the FCR they used. They were therefore excluded from the regression. Cases assessing the aquaculture sectors within a country were also excluded.

FTS, flow-through systems; NPPU, net primary production use; RAS, recirculating aquaculture systems.

Symbols '(+)' and '(–)' indicate an increasing or decreasing effect of the variable on the considered impact, respectively.

to the water pumping, whereas it may bring advantages in other impact categories, such as a reduced water dependence (see further details in Section Technology types). These are examples of parameters, on which researchers should focus to improve the environmental impacts of seafood farming (see Section Impact reduction potentials of aquaculture systems).

Distribution of environmental impacts within aquaculture systems

The life cycle of an aquaculture production system includes several stages and multiple components, which we divided into feed production, seafood farming (including hatchery and grow out), energy supply (electricity and fuel consumption), chemical use (including fertilizers, antifouling agents, antibiotics and other medical agents or chemical products), infrastructures (including buildings and equipment), packaging, distribution, consumption and end-of-life (e.g. recycling of the mussel shells or valorization of fish processing residues). Figure 4 provides an overview of those components over the life cycle of aquaculture systems.

Contribution of different system components

Large environmental impacts may stem from specific stages or components within the life cycle of the aquaculture systems (like feed production, energy supply or fish production) and thus constitute environmental hotspots of the systems. Table 2 reports the degree of consensus relative to the identification of such hotspots, as explicitly stated in the retrieved LCA studies. They are further discussed in the following subsections.

Seafood farming stage

In 72% of the studies, the production stage is a key driver of aquatic eutrophication impacts (Table 2) due to nitrogen and phosphorus emissions from uneaten feed and fish faeces. This impact category has been identified as one of the most important when studying aquaculture production (see Section Overall environmental performances; Mungkung *et al.* 2006; Efole Ewoukem *et al.* 2012; Aubin & Fontaine 2014). Therefore, reducing the nutrient emissions from seafood farming is a key factor for developing more sustainable aquaculture production systems (Grönroos *et al.* 2006; Phong *et al.* 2011).

In 75% of the studies, the production stage is also identified as the main source of water dependence (Table 2). This impact category, specific to aquaculture production, refers to the water input relative to the fish production in mass of biota (Aubin *et al.* 2009). By better combining water management and nutrient input systems, an improved aquaculture production could thus be possible (Efole Ewoukem

et al. 2012; Jerbi *et al.* 2012; Mungkung *et al.* 2013). However, it is important to evaluate whether such measures improve few impact categories (here aquatic eutrophication and water dependence) at the expense of others (e.g. ecotoxicity or biodiversity impact categories). This might create environmental burden-shifting, which should be avoided by assessing a broad spectrum of environmental problems when performing life cycle assessment (see Bohnes & Laurent 2018).

Feed production and influence of FCR

As shown in Table 2, feed production is found to be a key driver of cumulative energy demand (58% of the studies), net primary production use (86% of the studies), acidification (63% of the studies) and climate change (56% of the studies). The FCR is believed to be the main cause of these results. Indeed, 56% of the studies have explicitly stated that FCR has a main influence on the environmental impacts (Table 2) and, from the statistical analysis performed in Table 1, FCR was found to be a statistically significant parameter for explaining three major impact categories.

The FCR reflects the quantity of aquafeed needed per animal weight gain during production and is specific to a farming site. It is influenced by multiple factors, like the feed composition, the technology used, the fish species and the mortality at the site (Pelletier *et al.* 2009). All these factors offer possibilities for improvements that should be considered to overall decrease the FCR. Specific improvements related to decreasing impacts of feed production are further discussed in Section Improving feed production.

Energy supply systems

The choice of energy supply is important for the environmental performance of aquaculture systems. Over a third of the studies concluded that the energy context, including the geographical situation (determining the composition of the electricity grid mixes), had an influence on the environmental impacts – see Table 2 (among others: Aubin *et al.* 2009; Ayer & Tyedmers 2009; Aubin & Fontaine 2014). It is worth highlighting that this conclusion has not only been drawn about farms using recirculating aquaculture systems, but also when considering flow-through floating tanks (McGrath *et al.* 2015), traditional and cascade flow-through systems (Jerbi *et al.* 2012), offshore aquaculture systems (García García *et al.* 2016) or shellfish production farms (Lourguioi *et al.* 2017). Indeed, the different electricity production means present considerably different environmental impacts because the different energy sources and technologies have distinct emissions and resource uses. For example, fossil-fuel-based electricity production (such as coal or natural gas power plants) has much higher climate change impacts than electricity mixes based on

Figure 4 Life cycle of aquaculture systems broken down in its main components. Note the differences in system boundaries between limited cradle-to-farm-gate systems (grey dotted frame), complete cradle-to-farm-gate systems (black dotted frame) and complete life cycle systems (thick black line).

Table 2 Summary of the qualitative meta-analysis conducted on the studies (number of studies eligible to each statement stated in brackets)

<i>Share of studies that reports that...</i>	
... farming stage is a key driver of aquatic eutrophication (53 studies)	72%
... farming stage is a key driver of water dependence (12 studies)	75%
... feed production is a key driver of net primary production use (21 studies)	86%
... feed production is a key driver of acidification (48 studies)	63%
... feed production is a key driver of cumulative energy demand (38 studies)	58%
... feed production is a key driver of climate change (55 studies)	56%
<i>Share of studies that reports that...</i>	
... FCR has a major influence on the impacts (48 studies)	56%
... energy context has a major influence on the impacts (55 studies)	35%
... infrastructures accounts for at least 5% in at least one impact category (25 studies)	84%
... chemicals/fertilizers accounts for at least 5% in at least one impact category (18 studies)	78%

hydropower, solar power or wind power, whereas the opposite tends to be observed for metal depletion (Laurent *et al.* 2018). Therefore, the choice of the country is crucial for new farm installations, and installing on-site renewable electricity structures should be an option to consider. Additionally, the importance of FCR has been reported to decrease when the system has more energy inputs due to a burden-shifting from feed production to energy demand (Ayer & Tyedmers 2009; Samuel-Fitwi *et al.* 2013b), which could result in a decrease in overall impacts if the energy supply presents low environmental impacts.

Importance of often-neglected components

While all the studies considered the production stage, the feed production and the energy supply, only a few of them explicitly included the infrastructures and the chemicals used during the production (see Fig. 4). In our review, 33 studies included infrastructures and 25 of them conducted a contribution analysis. Among the latter, 84% reported that infrastructures accounted for more than 5% of total

life cycle impacts in at least one impact category. Contributions of up to 60% from infrastructures were even reported in the case of complex technological systems such as aquaponics (Forchino *et al.* 2017). Considering the important contributions that they may have in various systems and regarding different environmental impacts, infrastructures should by default be included in LCA of aquaculture systems, irrespective of the technology under study and the impact categories included.

Similarly, 35 studies included the production and use of chemicals in their assessment, and among the 18 of them that conducted a contribution analysis, 78% found out that these accounted for 5% or more in at least one impact category (see Table 2). In particular, some chlorine products used as disinfectants appeared to be toxic for humans and local organisms (Henriksson *et al.* 2015). However, these environmental impacts are seldom accounted for in LCA studies, as only 18 of 55 studies encompassed some chemicals used and performed contribution analyses to evaluate their influence (studies performing LCA of aquafeed only are not considered here). Further research should therefore focus on including the production and use of chemicals, which can be comprehensively assessed in LCA studies to identify the most environmental-friendly solutions, for example new therapeutants or vaccines (Henriksson *et al.* 2017a).

Importance of a full life cycle perspective

To conduct a comprehensive study and avoid environmental burden-shifting from one impact category to another, all the components of a system should be included in an LCA (Hellweg & i Canals 2014; Ziegler *et al.* 2016). However, most of the retrieved studies were found to only cover a cradle-to-farm-gate perspective and therefore neglected the packaging, distribution, consumption and end-of-life of the seafood (see Fig. 4). Only 16 of 55 studies had broader system boundaries than the cradle-to-farm-gate perspective (the 10 studies performing LCA of aquafeed only are not considered here). In spite of diverging conclusions, 11 of these studies reported a strong influence on the impact results from one or more processes in these post-farm stages. Six studies additionally highlighted the importance of setting up comprehensive system boundaries and recommended to adopt a full life cycle perspective (Aubin *et al.* 2006; Iribarren *et al.* 2010b; Pahari *et al.* 2016; Abdou *et al.* 2017, 2018; Fréon *et al.* 2017). While some postfarm stages, such as transportation, increase the environmental impacts, others, in particular in the end-of-life of the products (usually considered as by-products), can bring environmental benefits, like reuse or energy recovery processes from disposal of food waste (Iribarren *et al.* 2010a). Only the inclusion of a full life cycle can allow identifying such

environmental trade-offs potentially arising from aquaculture systems.

Comparative performances of aquaculture systems

Comparisons across aquaculture types and intensities

In most of the LCA studies conducted on aquaculture systems, the aim was to compare different intensities, technologies, and/or culture types in order to identify the most environmental-friendly ways of producing seafood (see Table S2). The findings of these studies are analysed in the following subsections.

Intensity of aquaculture systems

Of the 179 retrieved cases, 53% of them performed an assessment of an intensive system, 22% of a semi-intensive system and 14% of an extensive system (the remaining fraction being generic systems averaging more than one intensity type). Yet, this conventional way to categorize aquaculture production hides important differences among systems. Indeed, the group 'intensive systems' for instance gathers at the same time poorly managed production farms with excessive density of fish, and highly optimized, state-of-the-art technologies with good management of resources and fish. Therefore, it is not surprising that among the studies that have focused on comparing cases with different intensities, the findings differ considerably. While some studies did not find clear correlations between the intensity of the systems and the level of environmental impacts (Samuel-Fitwi *et al.* 2013b; Henriksson *et al.* 2015, 2017b), others reported that intensification of production caused an increase in emissions per functional unit (Cao *et al.* 2011; Efole Ewoukem *et al.* 2012; Samuel-Fitwi *et al.* 2013c; Yacout *et al.* 2016).

Analysing the pool of studies retrieved in the current review, intensive systems seem to have higher impacts than low-intensity systems in global impact categories (e.g. climate change) whereas they seem to perform equally or even better with respect to more local and regional impacts (e.g. aquatic eutrophication and water use) – see Figure S1. This observation is in line with several studies, which evidenced that the intensification of the production leads to an environmental burden-shifting from local to regional and global impacts (Aubin *et al.* 2006; Ayer & Tyedmers 2009; Pelletier & Tyedmers 2010; Samuel-Fitwi *et al.* 2013c; Dekamin *et al.* 2015). Indeed, more intensive systems typically require more energy for pumping water and, if the energy system relies on fossil fuels (like electricity production from coal), this translates into higher climate change and acidification impacts (global and regional). Filtering of water limits aquatic eutrophication impacts and freshwater use to levels similar to those observed for less intensive aquaculture systems. However,

the intensive systems assessed and compared in this sample of studies were not state-of-the-art intensive technologies. The latter would increase productivity while lowering impacts per functional unit thanks to their better optimization of the resources, such as freshwater, and their reduced interactions with the local ecosystems (Wilfart *et al.* 2013; Boxman *et al.* 2016).

Technology types

Escapes of farmed fish are an important issue in aquaculture because of the increasing risk of spreading pathogens and the potential disturbance of the natural balance caused in the area of escape, such as introduction of new predators, invasive species or genomic differences (Naylor *et al.* 2000). To reduce the interactions between farmed and wild fish, aquaculture technological advancements currently focus on developing closed-systems with technologies such as recirculating aquaculture systems (RAS) (Ayer & Tyedmers 2009; Pelletier & Tyedmers 2010; Henriksson *et al.* 2015, 2017b). In addition to lowering the risk of escapes, closed aquaculture systems offer better opportunities to reduce the nutrient emissions in the local environment and thus reduce the aquatic eutrophication impacts, because of their higher control of water effluents (Martins *et al.* 2010). This conclusion differs with the results presented in Table 1, which suggest that RAS increases eutrophication impacts compared to other technologies. This is explained by the difference in perspective between our statistical analysis, where studies are assessed altogether as a pool, and the current section which addresses studies' results individually, hence reducing uncertainties across the studies and drawing more reliable conclusions. Finally, they have better pathogen control due to the sterilization of incoming water, which reduces the mortality and thus increase the productivity of the farm (Klinger & Naylor 2012). It should be noted that extreme mortality events are not taken into account into the studies; only the average production mortality, for instance due to stress or water quality deterioration, is considered.

However, these technologies usually have a higher energy demand (Ayer & Tyedmers 2009), and studies that compare RAS with other technologies have concluded that RAS do not bring environmental benefits for all environmental impact categories, typically not for cumulative energy demand and climate change (Aubin *et al.* 2006, 2009; Ayer & Tyedmers 2009; Samuel-Fitwi *et al.* 2013b; Avadí *et al.* 2015). Such findings can also be observed when extracting the impact results from the studies included in the current review, as illustrated in Figure S2. RAS are thus found to generally have higher impacts than other systems with the exception of aquatic eutrophication and water dependence impacts, where they have lower impacts, and NPPU, where they have similar impacts.

Albeit being popular, RAS are not the only existing closed-system technology. Floating bags thus have been reported to show environmental benefits because of their efficient control of nutrient emissions (closed-system) while keeping a low energy demand (Ayer & Tyedmers 2009). In contrast, other technologies, such as cage farming, have been demonstrated to result in larger nutrient emissions than pond farming, where water management is easier (Henriksson *et al.* 2017b).

In parallel to developing new technologies, some solutions have been studied to reduce impacts of existing ones, such as a RAS based on a new Danish concept with a low energy consumption (d'Orbcastel *et al.* 2009) or the use of more environmentally sustainable materials like copper-alloys instead of nylon for net-pens thanks to the absence of antifouling coatings (Ayer *et al.* 2016).

Monoculture versus polyculture

Of the 179 cases, 79% exclusively assessed monoculture, 12% polyculture and 9% were generic studies including both (such as country-scale studies). Conclusions typically vary between studies that compare monoculture and polyculture systems. Some studies could not conclude on superiority of either, typically showing better environmental performances for monoculture systems in several impact categories because of their high productivity, but also a larger energy intensity (Baruthio *et al.* 2008; Aubin *et al.* 2015). In contrast, other studies showed polyculture systems to have lower environmental impacts thanks to their potential for species complementarity (Kluts *et al.* 2012; Mungkung *et al.* 2013; Medeiros *et al.* 2017). To maximize the benefits, the set of species grown together needs to be chosen with different feeding habits so that they can benefit from each other's by-products and reuse nutrients across taxa (Auburn University 2017). For example, nutrient emissions could be reduced by producing fish along with molluscs and algae, which will capture and use some of the released nutrients. This latter setting also belongs to integrated multitrophic aquaculture systems, which are further discussed in Section Integrated multitrophic aquaculture: a promising approach?.

Species and culture environments

As discussed in Section Overview of assessed cases and statistical analysis, the choice of the species has a statistically significant influence on the results for climate change, aquatic eutrophication, acidification, cumulative energy demand and NPPU (Table 1). It means that, on a mass unit basis, some kinds of seafood have lower environmental impacts than others. In their country-scale studies, Seves *et al.* (2016) thus showed that salmon is the fish species with the lowest environmental impacts among farmed fish consumed in the

Netherlands, and Henriksson *et al.* (2017b) concluded on the superiority of catfish over carps and tilapia for the Indonesian consumption. On the other hand, Pelletier *et al.* (2009) found out that in salmon production, environmental performance followed a similar pattern between regions even though the production techniques differed. These results therefore suggest that some impact specificities are linked to species, as statistically demonstrated in Table 1. However, although the species might have specific influence on impacts, other parameters may alter the impact results too, such as the different needs of the species in the specific situation of the study potentially varying between countries or technologies.

Improving feed production

As stated in Section Feed production and influence of FCR, feed production was found to be a key contributor to the environmental impacts of aquaculture systems in a majority of the reviewed LCA studies (see Table 2). As a consequence, solutions to reduce the impacts associated with feed production have been explored, like new feed formulations (Ayer & Tyedmers 2009; Pelletier & Tyedmers 2010; Iribarren *et al.* 2012b; Santos *et al.* 2015; García García *et al.* 2016; Yacout *et al.* 2016; Abdou *et al.* 2018; Henriksson *et al.* 2017b). The results of different diets are compared in Figure 5, with all the cases of aquafeed available in Table S3.

The impacts of conventional aquafeed mainly stem from the production of the raw materials, and especially the fish meal and fish oil (FMFO) ingredients because of intensive fuel use of fisheries vessels (Iribarren *et al.* 2012b) or low efficiency of processing plants (Fréon *et al.* 2017). Additionally, the aquafeed industry strives to move towards less dependence on marine resources, because of their scarcity and their higher price (Papatriphou *et al.* 2004). Therefore, recent studies have been focusing on replacing those ingredients by substitutes. Crop-based proteins have thus been assessed as a potential surrogate, with 7 of 10 studies concluding that the substitution significantly improved the results (Grönroos *et al.* 2006; Pelletier & Tyedmers 2007, 2010; Samuel-Fitwi *et al.* 2013a; Avadí *et al.* 2015; Nhu *et al.* 2016; Smáráson *et al.* 2017) while the remaining three reported that environmental impacts were comparable (Papatriphou *et al.* 2004; Boissy *et al.* 2011; Iribarren *et al.* 2012b). Indeed, while climate change and cumulative energy consumption usually decrease, some other impact categories might increase because of other factors (e.g. acidification due to NH₃ emissions during agriculture). However, it should be noted that not all crop-based ingredients performed equally with respect to environmental impacts and therefore not all turn out to be better than FMFO

ingredients (Nhu *et al.* 2016). An important risk is to generate environmental burden-shifting, for example with an increase in the land use and aquatic eutrophication impacts (see Fig. 5). In comparison to FMFO, crop-based ingredients require agricultural processes, which are associated with larger impacts on land use (to grow products) and aquatic eutrophication potential (via use of fertilizers) (Boissy *et al.* 2011). Although not assessed in any of the retrieved studies, crop-based ingredients might also have higher toxic impacts than marine-based ingredients because of the use of pesticides. This calls for comprehensive studies to assess the environmental trade-offs between crop-based and marine-based ingredients with coverage of a large spectrum of environmental impacts to avoid burden-shifting (see also Bohnes & Laurent 2018).

Other substitutes to FMFO are also possible and have been assessed in previous studies, including seafood by-products (Papatriphou *et al.* 2004; Pelletier & Tyedmers 2007), food waste from human communities (like fishery vessels in Strazza *et al.* 2015), fly-larvae-based feed (Smáráson *et al.* 2017) or seaweed-based feed (Seghetta *et al.* 2017) – see Figure 5 for comparative results. Using seafood by-products to replace FMFO shows lower environmental impacts in climate change, energy use and NPPU (Papatriphou *et al.* 2004), but only when the by-products originate from fisheries with low fuel consumption (Pelletier & Tyedmers 2007). Food waste from human consumption is found to have lower environmental impacts in all climate change, nonrenewable energy consumption and water depletion (Strazza *et al.* 2015; see Fig. 5). Black-fly-larvae-based aquafeed also seems promising to reduce impacts compared to FMFO, including climate change and acidification impacts, as well as human toxicity, marine aquatic ecotoxicity and abiotic depletion (Smáráson *et al.* 2017). A major drawback about the use of fly-larvae was identified to be the higher energy demand than for FMFO, although this tendency may be explained by the immaturity of this emerging feed production pathway and could be expected to be addressed in future developments (Smáráson *et al.* 2017).

In parallel to finding new substitutes to FMFO, another explored solution to decrease feed impacts has been to reduce the impacts of FMFO itself. For example, studies have suggested exploiting marine feed sources from lower trophic levels (Ellingsen & Aanonsen 2006; McGrath *et al.* 2015), or improving the quality of the production of FMFO by having cleaner, newer technology factories to produce more in each factory (because of their current drastic overcapacity in some countries – Fréon *et al.* 2017). Only the latter alternative has been thoroughly studied in terms of environmental impact coverage, and results showed an improvement in all impact categories included in the ReCiPe 2008 methodology (Goedkoop *et al.* 2013) with for

Figure 5 Ratio of the environmental impacts of conventional diet (Conv.) compared to those of different feed diets for seven selected impacts categories. Impact scores are expressed per unit of kilogram produced. CED, cumulative energy demand; FMFO: fish meal and fish oil; NPPU, net primary production use. (+) Conv/Low FMFO; (□) Conv/By-product; (△) Conv/Organic; (◇) Conv/Food waste and (○) Conv/Fly larvae.

example reductions of 50% in climate change and aquatic eutrophication impacts, 80% in water use and 60% in fossil depletion.

Regardless of above and because of the found importance of FCR (see Section Feed production and influence of FCR), a better substitute is a substitute which would also increase feed efficiency, because it would decrease the mass of feed needed per mass of fish produced which in turn would also decrease nutrient load during the aquaculture production phase since these primarily stem from release of uneaten feed and faeces (Grönroos *et al.* 2006). Such aspects have not been well included in previous studies. Therefore, there is a need for more LCA studies about aquafeed that involve fish nutrition experts and thus avoid the risk of problem-shifting if the new diet results in a higher FCR (Pelletier & Tyedmers 2010; Avadí *et al.* 2015; McGrath *et al.* 2015; Smárason *et al.* 2017).

Integrated multitrophic aquaculture: a promising approach?

Integrated multitrophic aquaculture (IMTA) consists in combining the production of species from different trophic

or nutritional levels, such as seafood and algae. It may have the potential to decrease environmental impacts if the different species are wisely selected and combined (Bostock *et al.* 2010). The production of the two taxa is integrated to optimize the use of water, feed and fertilizers. It can for example be done by integrating a substrate on which natural food can grow or by adding filter-feeding fish (Santos *et al.* 2015). Two main kinds of IMTA exist: aquaponics and IAA, on which two and five LCA studies have been conducted until now, respectively (see Table 1).

Aquaponics consists of combining fish farming with hydroponics, the method of growing plants without soil. However, energy use and feed production remain the source of major environmental issues for these systems (Boxman *et al.* 2016; Forchino *et al.* 2017). To address these, optimization of management practices has been tested with focus on reducing FCR, which, combined with an increasing energy efficiency, by optimizing the water pumping, leads to important decreases in the impacts of the system (Boxman *et al.* 2016; Forchino *et al.* 2017). Additionally, infrastructures are found to be a major environmental hotspot in some aquaponics systems, and the choice of less impacting materials was reported to help

decrease the environmental impacts of fish, algae and plants production (Forchino *et al.* 2017).

Contrarily to aquaponics, which are modern techniques and rely on highly controlled environments, IAA has been used in China for centuries, with for instance mulberry plot-fishponds or bamboo plot-fishponds (Min & Hu 2017). In general, they show lower environmental impacts than the other alternative systems (Phong *et al.* 2011; Kluts *et al.* 2012; Henriksson *et al.* 2015; Jonell & Henriksson 2015). The reduced use of feed is the main source of environmental impact reduction (Kluts *et al.* 2012). An exception remains with aquatic eutrophication impacts, which turn out to be higher for the integrated systems if the input of natural fertilizer (usually manure) is not optimized. These cause a higher nutrient discharge to rivers during water replacement (Kluts *et al.* 2012), although this excess of nutrients has been reported to be recyclable to limit the high aquatic eutrophication (Henriksson *et al.* 2015). IAA systems therefore seem to be a promising way to manage fish farming and, owing to the very limited number of LCA studies performed on those systems, more LCA application should accompany their development. Identification of the most problematic stages or components of the systems may thus help construct more environmental-friendly systems. Additionally, collaborating with fish biologists could result in identification of optimal combinations of species.

Relevance of LCA as a policy- and decision-making tool in aquaculture

As demonstrated in the previous sections, LCA is a useful tool to identify the environmental hotspots of aquaculture systems and to compare them with each other with respect to their embedded environmental impacts. This can provide useful information to policymakers and decision-makers when it comes to encouraging development of specific types of farm installations or to introducing regulations on excessively polluting processes. It supports identification of environmental hotspots to focus development of more eco-efficient aquaculture systems and can also be useful to help consumers select products, which meet minimum environmental requirements, for example thanks to the use of LCA for ecolabelling (Hauschild *et al.* 2018).

Impact reduction potentials of aquaculture systems

From the analysis of the 65 articles conducting an LCA of aquaculture systems, several potential ways to reduce environmental impacts of aquaculture can be identified. In general, wastewater and sludge management, feeding management, nutrient management and productivity are pointed out as main causes of environmental impacts from aquaculture systems. Environmental improvements on

these generic aspects should therefore be undertaken by the aquaculture industry. However, as noted in Sections Distribution of environmental impacts within aquaculture systems and Comparative performances of aquaculture systems, specificities of the aquaculture systems under study (e.g. type of technologies, location) may strongly influence the impact results. This calls for performing LCA studies that are as specific to the situations and contexts as possible to allow providing relevant decision support to aquaculture stakeholders.

For example, in a situation of a new farm design, the system characteristics are important for environmental performance of the system. Polyculture or IMTA should thus be preferred to monoculture, and closed-systems with low energy requirements, along with species that have low FCR, should be prioritized (see Section Improving feed production). The development of aquaculture management areas, where some infrastructures and equipment (like a processing plant) are shared by a group of farmers, seems promising to reduce the impacts for small producers (Lourguioi *et al.* 2017). The choice of aquafeed should additionally be done carefully, aiming for formulations with less FMFO (see Section Improving feed production).

Existing systems can be improved by the implementation of best management practices (Avadí *et al.* 2015; Abdou *et al.* 2018; Henriksson *et al.* 2017a) and the use of probiotics (live bacteria and yeasts that are assumed to be beneficial in preventing diseases) (Iribarren *et al.* 2012a). Both would improve disease prevention and therefore increase productivity of the farm, while reducing use of antibiotics that create antimicrobial resistance (qualified as one of the biggest threats to global health and food security today by the World Health Organization – WHO 2017). In addition, best effluent management (such as conventional practices with the addition of effluent treatment with constructed wetlands) would directly reduce the release of nutrients in the surrounding environment (Santos *et al.* 2015). Albeit controversial, genetically improved species have also turned out to show interesting advantages although the consequences on natural environment from potential escapes of such modified organisms have not yet been assessed (Besson *et al.* 2016; Henriksson *et al.* 2017a). Finally, utilization of coproducts and by-products was found to have important potentials to decrease environmental impacts, particularly when transformed in a way that increases the output going to direct human consumption (Winther *et al.* 2009; Iribarren *et al.* 2010a; Pelletier & Tyedmers 2010).

What can we learn from macro scale and future-oriented studies?

Large-scale studies are especially useful for policy-making, for which evaluation of existing regulations or

implementation of new ones can be assessed at national or regional scales (Gibon *et al.* 2015). Among the 65 reviewed studies, six LCA studies adopted a country-scale perspective and four others focused on a whole sector. At sector level, the LCA studies are effective at identifying high-impact practices that need to be improved (Jonell & Henriksson 2015; Nhu *et al.* 2016) as well as pointing out the less efficient subsectors (Iribarren *et al.* 2010c). For example, in their study on the entire mussel cultivation in Spain, Iribarren *et al.* (2010c) identified the dispatch centres, that is centres where mussels are purified, sorted and calibrated, as the most impactful subsector and thus as the place for policymakers to prioritize their efforts on reducing environmental impacts.

National studies can be consumption- or production-oriented and are useful when used to inform policymakers about the environmental sustainability of their countries. These can help them take nationwide or sectorwide actions by assessing the sustainability of current seafood consumption in a country in the case of consumption-oriented studies (Seves *et al.* 2016) or giving an overview of the environmental performance of a country production facilities in the case of production-oriented studies (Winther *et al.* 2009). The World Fish Centre and Conservation International thus exploited the potential of this type of study in a report (Hall *et al.* 2011 – not included in the current review because lacking peer-review), in which they conducted an LCA on over 80% of the world aquaculture production to support recommendations for stakeholders in several countries. Results of large-scale studies can thus be used in the development of more sustainable diets in specific countries or regions, based on knowledge about the impacts of the actual seafood sold in that area (Farmery *et al.* 2017), or in advising policymakers regarding governmental plans for aquaculture sectorial development. For example, Henriksson *et al.* (2017b) performed a country-level, foresight study and compared different scenarios of seafood development in Indonesia for the next 15 years, using projections from Tran *et al.* (2017). They concluded that none of the tested scenarios would satisfy the government plan for development of the aquaculture sector in terms of resource needs and recommended to prioritize more resource-efficient species and more sustainable aquaculture practices by among others farmer training, improved water management or the use of more environmental-friendly feeds. Such insights are highly useful for authorities, who may thus want to revise their planning for the future development of the entire sector. This is particularly relevant for developing countries, like Indonesia, where fast growth of the aquaculture sector is anticipated to contribute fighting nutrition challenges (FAO 2016; Tran *et al.* 2017). Future-oriented, country-level and/or sector-level LCA studies are thus essential to anticipate future

environmental trade-offs and burden-shifting and help policymakers design adapted development plans for low-impact aquaculture systems. However, the LCA methodology, which has traditionally been applied at product level, is not always directly applicable on these large-scale, foresight systems. More research to enable the conduct of such studies is therefore needed.

Limitations of LCA to assess seafood production sustainability

Life cycle assessment is a useful tool to improve sustainability in aquaculture thanks to its full life cycle perspective and its broad environmental impacts coverage. However, the impact categories currently covered by LCA and supported by existing LCA software remain limited in the perspective of aquaculture systems. A number of issues specific to aquaculture are thus not addressed, like destruction of local environment due to the mix of farmed and wild populations due to escapes (Naylor *et al.* 2000). In addition, some existing impact categories have a limited coverage of the causes of impacts. For example, in the assessment of toxicity-related impacts, relevant substances like antibiotics cannot yet be assessed, even though they may increase impacts on human health via antimicrobial resistance (Watts *et al.* 2017). Research is therefore needed to complete the set of methods for life cycle impact assessment and thus allow more comprehensive and accurate assessments of aquaculture systems. Meanwhile, we recommend combining LCA studies with other types of assessment tools to address yet-uncovered issues, such as the use of risk assessment to account for effects from antimicrobial resistance (see further details in Bohnes & Laurent 2018).

Additionally, the current availability of data concerning seafood production in LCA inventory databases is low (Farmery *et al.* 2017), and experts should therefore tackle that gap by gathering aquaculture data and populate such databases. Their additions to the main life cycle inventory databases would make aquaculture assessments easier and enable a wider use of LCA in relevant regions, like Asia, where there is a current lack of LCA practice. Such efforts should also be coupled with significantly improving transparency of LCA studies conducted on aquaculture systems. As pointed out in other fields, the current lack of clarity and improper documentation of assumptions and data sources is an important barrier to the comparability of studies, thus decreasing considerably the credibility and usefulness of LCA studies in the long term and for the research community in general (Brandão *et al.* 2012). When such reporting standardization is effective, harmonization of the studies will be possible and thus enable the conduct of full-fledged meta-analyses.

Conclusions and recommendations

The production of seafood from aquaculture is the fastest growing food production in the world and should be developed to be more environmentally sustainable. In our study, we reviewed 65 papers that reported LCA of aquaculture systems and aquaculture feed. At global scale, Asian and African aquaculture systems are much underrepresented in past LCA studies, even though Asian aquaculture production accounts for more than 90% of global production and seafood as an important protein source participates to food security in some African countries; more studies of Asian and African systems are therefore warranted.

Through the conducted statistical analysis, the influence of the species farmed and the FCR was found particularly determinant for environmental performances of the systems. Several ways to reduce the impacts of existing or new aquaculture systems still exist, and key recommendations are recapped below based on the findings and detailed guidance provided in Sections Overview of assessed cases and statistical analysis, Distribution of environmental impacts within aquaculture systems, Comparative performances of aquaculture systems, Relevance of LCA as a policy- and decision-making tool in aquaculture:

- We recommend that seafood farmers focus on improving the general management of their production systems, with a specific attention to the management of nutrients, the water management and the choice of adapted and FCR-optimized aquafeed (see Sections Contribution of different system components and Improving feed production). Some technologies have a great potential to improve environmental impacts, such as polyculture, and in particular IMTA, or low energy RAS (see Section Comparative performances of aquaculture systems).
- We recommend that policymakers base their regulations on LCAs to improve the environmental impacts of existing and future aquaculture systems. Such regulations should be backed-up by nationwide and/or sectorwide LCA studies to identify hotspots, (see Section What can we learn from macro scale and future-oriented studies?). Such regulatory efforts should be complemented with initiatives that sensitize the public to sustainable seafood production, which may create market-driven call for more sustainable production schemes; the use of LCA-based ecolabelling can help in such initiatives (see Section Impact reduction potentials of aquaculture systems).
- We recommend that seafood technology/system developers systematically include life cycle assessment to assist them in finding as environmentally sustainable systems/technologies as possible when working on improving productivity. As part of our review, environmental hotspots were identified for a number of specific technologies and systems; these may also serve as basis to improve existing

systems and develop new ones (see, e.g. Sections Contribution of different system components and Comparisons across aquaculture types and intensities).

- We recommend that consistent and detailed guidelines on how to apply the LCA methodology to aquaculture systems be developed to improve the consistency and comparability of studies (see Bohnes & Laurent 2018). To reach that aim, the transparency in reporting the scope and inventory phases of LCA studies should be a priority for LCA practitioners. LCA method developers should additionally extend the range of existing impact categories to include new impact categories specific to the aquaculture sector, for example enabling assessing the reduction of antimicrobial resistance to unveil potential environmental trade-offs with commonly assessed categories of impacts (see Bohnes & Laurent 2018).

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Ratios of the environmental impacts of intensive aquaculture systems over those of either semi-intensive or extensive aquaculture systems.

Figure S2. Ratio of the environmental impacts of recirculating aquaculture systems (RAS) compared to other aquaculture systems (total of six studies).

Table S1. List of the main criteria used in for the mapping of the scenarios and their definition.

Table S2. List of 179 scenarios assessing environmental impacts of aquaculture systems (total of 65 retrieved studies published up to mid-2017).

Table S3. List of the feed scenarios analyzed in that literature review.

Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development

Supplementary information

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This document includes:

• Supporting Figures S1 and S2	Page S2
• Supporting Tables S1 to S3	Pages S3-S13
• Supporting references	Pages S14-S18

SUPPLEMENTARY FIGURES

Figure S1: Ratios of the environmental impacts of intensive aquaculture systems over those of either semi-intensive or extensive aquaculture systems. The dots represent the results found within a study (total of 4 studies). The crosses represent the average and the whiskers the standard error. Note the logarithmic scale on the y-axis. A ratio higher (lower) than 1 means that the intensive system has higher (lower) environmental impacts than the systems with other intensities. CED = Cumulative energy demand; NPPU = Net primary production use.

Figure S2: Ratio of the environmental impacts of recirculating aquaculture systems (RAS) compared to other aquaculture systems (total of 6 studies). Comparisons are made within each study. The crosses represent the average and the whiskers the standard error. It is plotted in a logarithm base 10 scale and a ratio higher than 1 means that the RAS has higher environmental impacts and lower than 1 that the RAS has lower environmental impacts than the system it is compared to. In bracket is indicated the number of entries available for each impact category. CED = Cumulative energy demand; NPPU = Net primary production use.

SUPPLEMENTARY TABLES

Table S1: List of the main criteria used in for the mapping of the scenarios and their definition

Criteria	Sub-categories	Definition / description	Source
Culture intensity	Intensive	Production relying only on feeding activity + high stock density	EC 2017
	Semi-intensive	Production relying on natural food & supplementary feeding + relatively low stocking density	
	Extensive	Production relying on natural food (absence of feeding activity) + low stocking density	
Culture diversity	Monoculture	Culture of a single species of an organism in a culture system	FAO 1987
	Polyculture	Culture of several species in the same waterbody	
Culture environment	Freshwater culture	The cultivation of aquatic organisms where the end product is raised in freshwater	(EC 2017)
	Coastal culture	The cultivation of aquatic organisms where the end product is raised in coastal water (brackish water and seawater)	
Species	Freshwater fish	Fishes that live exclusively in freshwater.	(UNIVERSIDADE DE ÉVORA 2015)
	Diadromous fish	Fishes that live both in freshwater and saltwater, at different stages of their life cycle.	
	Marine fish	Fishes that live exclusively in saltwater.	
	Crustaceans	/	
	Molluscs	/	
Technologies	Ponds/tanks	/	
	Nets/cages	/	
	Flow through systems (FTS)	Fish are stocked densely in a long and narrow pond or tank in which there is an abundant continuous water flow	(Váradi 2017)
	Recirculating aquaculture system (RAS)	Reusing the water in the production system by the use of mechanical and biological filters.	(Bregnballe 2015)
	Others		
Integrated multi-trophic	<i>General definition</i>	Including organisms from different trophic levels of an ecosystem (e.g. fish, shellfish,	(EC 2017)

aquaculture (IMTA)		algae), so that the by-products of one become the inputs of another.	
	Integrated agriculture-aquaculture (IAA)	The diversification that comes from integrating crops, vegetables, livestock, trees and fish imparts stability in production, efficiency in resource use and conservation of the environment.	(FAO 2001)
	Aquaponics	A system of aquaculture in which the waste produced by farmed fish or other aquatic creatures supplies the nutrients for plants grown hydroponically, which in turn purify the water.	(Oxford dictionaries 2017)

Table S2: List of 179 scenarios assessing environmental impacts of aquaculture systems (total of 65 retrieved studies published up to mid-2017). NA=Not available; NR=Not relevant.

ID	Reference	Species	Technology [†]	Country	Mono or Polyculture (Integrated Multi-Trophic Aquaculture [‡])	Intensity [§]	Scenario-specific parameters / focus of the study [¶]
1	(Abdou <i>et al.</i> 2017a)	European seabass	Net cages	Tunisia	M	SI	Comparison of species
2	(Abdou <i>et al.</i> 2017a)	Gilthead seabream	Net cages	Tunisia	M	SI	Comparison of species
3	(Abdou <i>et al.</i> 2017b)	Seabass and seabream	Cages	Tunisia	P	I	Depth: deep; production: low; FCR: low
4	(Abdou <i>et al.</i> 2017b)	Seabass and seabream	Cages	Tunisia	P	I	Depth: deep; production: low; FCR: high
5	(Abdou <i>et al.</i> 2017b)	Seabass and seabream	Cages	Tunisia	P	I	Depth: shallow; production: low; FCR: low
6	(Abdou <i>et al.</i> 2017b)	Seabass and seabream	Cages	Tunisia	P	I	Depth: shallow; production: high; FCR: high
7	(Abdou <i>et al.</i> 2017b)	Seabass and seabream	Cages	Tunisia	P	I	Depth: very deep; production: very high; FCR: high
8	(Aubin and Fontaine 2014)	Mussels	Bouchots	France	M	E	Technology hotspots
9	(Aubin <i>et al.</i> 2006)	Turbot	RAS	France	M	I	Emissions scenario A
10	(Aubin <i>et al.</i> 2006)	Turbot	RAS	France	M	I	Emissions scenario B
11	(Aubin <i>et al.</i> 2006)	Turbot	RAS	France	M	I	Emissions scenario C
12	(Aubin <i>et al.</i> 2009)	Rainbow trout	FTS	France	M	I	Comparison of technologies
13	(Aubin <i>et al.</i> 2009)	Turbot	RAS	France	M	I	Comparison of technologies
14	(Aubin <i>et al.</i> 2009)	Seabass	Net cages	Greece	M	SI	Comparison of technologies
15	(Aubin <i>et al.</i> 2015)	Tiger prawn, crabs, Tilapia and milkfish	Ponds	Philippines	P	E	Technology hotspots
16	(Avadi and Freon 2015)	Black pacu	Ponds	Peru	M	SI	Comparison of species
17	(Avadi and Freon 2015)	Rainbow trout	Cages	Peru	M	SI	Comparison of species
18	(Avadi and Freon 2015)	Red tilapia	Ponds	Peru	M	I	Comparison of species
19	(Avadi <i>et al.</i> 2015)	Black pacu	Ponds	Peru	M	SI	Aquafeed artisanal

20	(Avadi <i>et al.</i> 2015)	Black Pacu	Ponds	Peru	M	SI	Aquafeed commercial
21	(Avadi <i>et al.</i> 2015)	Rainbow trout	Cages	Peru	M	SI	Aquafeed artisanal
22	(Avadi <i>et al.</i> 2015)	Rainbow trout	Cages	Peru	M	SI	Aquafeed commercial
23	(Avadi <i>et al.</i> 2015)	Rainbow trout	Cages	Chile	M	SI	Aquafeed commercial
24	(Avadi <i>et al.</i> 2015)	Red tilapia	Ponds	Peru	M	I	Aquafeed commercial
25	(Avadi <i>et al.</i> 2015)	Red tilapia	Ponds	Peru	M	SI	Aquafeed generic
26	(Avadi <i>et al.</i> 2015)	Red tilapia	Ponds	Peru	M	I	Aquafeed generic
27	(Ayer and Tyedmers 2009)	Atlantic salmon	Net cages	Canada	M	SI	Comparison of technologies
28	(Ayer and Tyedmers 2009)	Arctic char	RAS	Canada	M	I	Comparison of technologies
29	(Ayer and Tyedmers 2009)	Atlantic salmon	FTS	Canada	M	I	Comparison of technologies
30	(Ayer and Tyedmers 2009)	Atlantic salmon	Floating bags	Canada	M	SI	Comparison of technologies
31	(Ayer <i>et al.</i> 2016)	Atlantic salmon	Net cages in copper-alloy mesh	Chile	M	SI	Comparison of technologies
32	(Ayer <i>et al.</i> 2016)	Atlantic salmon	Net cages in nylon mesh	Chile	M	SI	Comparison of technologies
33	(Baruthio <i>et al.</i> 2008)	Tiger prawn, crabs, Tilapia and milkfish	Ponds	Philippines	P	E	Technology hotspots
34	(Besson <i>et al.</i> 2016)	African catfish	RAS	The Netherlands	M	I	Technology hotspots
35	(Boissy <i>et al.</i> 2011)	Rainbow trout	FTS	France	M	I	Low fish meal feed
36	(Boissy <i>et al.</i> 2011)	Rainbow trout	FTS	France	M	I	Standard feed
37	(Boissy <i>et al.</i> 2011)	Atlantic salmon	Net cages	Scotland	M	I	Low fish meal feed
38	(Boissy <i>et al.</i> 2011)	Atlantic salmon	Net cages	Scotland	M	I	Standard feed
39	(Bosma <i>et al.</i> 2011)	Striped catfish	Ponds	Vietnam	M	I	Technology hotspots
40	(Boxman <i>et al.</i> 2016)	Tilapia	RAS	USA	P (AP)	I	Technology hotspots
41	(Cao <i>et al.</i> 2011)	Shrimps	Ponds	China	M	I	Cradle-to-farm gate
42	(Cao <i>et al.</i> 2011)	Shrimps	Ponds	China	M	SI	Cradle-to-farm gate
43	(Cao <i>et al.</i> 2011)	Shrimps	Ponds	China	M	I	Cradle-to-destination
44	(Cao <i>et al.</i> 2011)	Shrimps	Ponds	China	M	SI	Cradle-to-destination
45	(Chen <i>et al.</i> 2015)	Rainbow trout (large)	FTS	France	M	I	Comparison of species
46	(Chen <i>et al.</i> 2015)	Rainbow trout (pan-size)	FTS	France	M	I	Comparison of species
47	(Chen <i>et al.</i> 2015)	Rainbow trout (very large)	FTS	France	M	I	Comparison of species
48	(Dekamin <i>et al.</i> 2015)	Rainbow trout	FTS	Iran	M	I	Comparison of technologies
49	(Dekamin <i>et al.</i> 2015)	Rainbow trout	RAS	Iran	M	I	Comparison of technologies
50	(Dekamin <i>et al.</i> 2015)	Rainbow trout	Semi-closed RAS	Iran	M	I	Comparison of technologies
51	(d'Orbecastel <i>et al.</i> 2009)	Rainbow trout	FTS	France	M	I	Comparison of technologies
52	(d'Orbecastel <i>et al.</i> 2009)	Rainbow trout	RAS	France	M	I	Comparison of technologies

53	(Efole Ewoukem <i>et al.</i> 2012)	Tilapia + catfish	Ponds	Cameroon	P (IAA)	E	Pig manure as fertilizer
54	(Efole Ewoukem <i>et al.</i> 2012)	Tilapia + catfish	Ponds	Cameroon	P (IAA)	E	Pig and chicken manure as fertilizer
55	(Efole Ewoukem <i>et al.</i> 2012)	Tilapia + catfish	Ponds	Cameroon	P (IAA)	E	Pig manure as fertilizer and crop by-product as aquafeed
56	(Efole Ewoukem <i>et al.</i> 2012)	Tilapia + catfish	Ponds	Cameroon	P (IAA)	E	Wheat bran as aquafeed
57	(Ellingsen and Aanondsen 2006)	Atlantic salmon	NA	Norway	M	I	Comparison of different protein sources
58	(Forchino <i>et al.</i> 2017)	Rainbow trout	RAS	Italy	P (AP)	I	Media-Filled Beds Systems
59	(Forchino <i>et al.</i> 2017)	Rainbow trout	RAS	Italy	P (AP)	I	Rafts
60	(García García <i>et al.</i> 2016)	Gilthead seabream	Cages	Spain	M	SI	Technology hotspots
61	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Cages	Finland	M	SI	Comparison of technologies
62	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Funnels	Finland	M	SI	Comparison of technologies
63	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Ponds	Finland	M	I	Comparison of technologies
64	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Net cages	Finland	M	SI	FCR = 0.9
65	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Net cages	Finland	M	SI	FCR = 1.255
66	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Net cages	Finland	M	SI	FCR = 1.255 and soy as aquafeed
67	(Grönroos <i>et al.</i> 2006)	Rainbow trout	Net cages	Finland	M	SI	FCR = 1.53
68	(Henriksson <i>et al.</i> 2015)	Whiteleg shrimps	NA	Thailand	M	I	Comparison of technologies
69	(Henriksson <i>et al.</i> 2015)	Asian tiger shrimps	NA	Bangladesh	M	I	Comparison of technologies
70	(Henriksson <i>et al.</i> 2015)	Giant river prawn and Asian tiger shrimps	NA	Bangladesh	P	SI	Comparison of technologies
71	(Henriksson <i>et al.</i> 2015)	Giant river prawn and Asian tiger shrimps	NA	Bangladesh	P	SI	Comparison of technologies
72	(Henriksson <i>et al.</i> 2015)	Pangasius catfish	NA	Vietnam	M	I	Comparison of technologies
73	(Henriksson <i>et al.</i> 2015)	Whiteleg shrimps	Ponds	China	M	I	Comparison of technologies
74	(Henriksson <i>et al.</i> 2015)	Asian tiger shrimps	NA	Bangladesh	P	SI	Comparison of technologies
75	(Henriksson <i>et al.</i> 2015)	Whiteleg shrimps	Ponds	China	M	I	Comparison of technologies
76	(Henriksson <i>et al.</i> 2015)	Whiteleg shrimps	NA	Thailand	M	I	Comparison of technologies
77	(Henriksson <i>et al.</i> 2015)	Pangasius catfish	NA	Vietnam	M	I	Comparison of technologies
78	(Henriksson <i>et al.</i> 2015)	Tilapia	NA	China	M	I	Comparison of technologies
79	(Henriksson <i>et al.</i> 2015)	Tilapia	NA	China	M	SI	Comparison of technologies
80	(Henriksson <i>et al.</i> 2015)	Asian tiger shrimps	NA	Vietnam	M	SI	Comparison of technologies
81	(Henriksson <i>et al.</i> 2015)	Asian tiger shrimps	NA	Vietnam	M	I	Comparison of technologies
82	(Henriksson <i>et al.</i> 2015)	Whiteleg shrimps	NA	Vietnam	M	I	Comparison of technologies
83	(Henriksson <i>et al.</i> 2015)	Tilapia	Ponds	China	P (IAA)	I	Comparison of technologies
84	(Henriksson <i>et al.</i> 2015)	Tilapia	Ponds	China	M	E	Comparison of technologies
85	(Henriksson <i>et al.</i> 2015)	Pangasius catfish	NA	Vietnam	M	SI	Comparison of technologies
86	(Henriksson <i>et al.</i> 2015)	Giant river prawn	NA	Bangladesh	P	E	Comparison of technologies
87	(Henriksson <i>et al.</i> 2015)	Giant river prawn	NA	Bangladesh	P	E	Comparison of technologies

88	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Best management practices farming (economic allocation)
89	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Best management practices farming (mass allocation)
90	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Best management practices farming using G9 strain (economic allocation)
91	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Best management practices farming using G9 strain (mass allocation)
92	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Conventional farming (economic allocation)
93	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Conventional farming (mass allocation)
94	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Farming using G9 strain (mass allocation)
95	(Henriksson <i>et al.</i> 2017a)	Tilapia	Ponds	Egypt	M	I	Farming using G9 strain (economic allocation)
96	(Henriksson <i>et al.</i> 2017b)	Tilapia	Ponds	Indonesia	M	I	Future scenarios
97	(Henriksson <i>et al.</i> 2017b)	Tilapia	Cages	Indonesia	M	I	Future scenarios
98	(Henriksson <i>et al.</i> 2017b)	Common carp	Cages	Indonesia	M	I	Future scenarios
99	(Henriksson <i>et al.</i> 2017b)	Clarias	Ponds	Indonesia	M	I	Future scenarios
100	(Henriksson <i>et al.</i> 2017b)	Pangasius	Ponds	Indonesia	M	I	Future scenarios
101	(Henriksson <i>et al.</i> 2017b)	Pangasius	Cages	Indonesia	M	I	Future scenarios
102	(Henriksson <i>et al.</i> 2017b)	Milkfish	Ponds	Indonesia	P	E	Future scenarios
103	(Henriksson <i>et al.</i> 2017b)	Grouper	Cages	Indonesia	M	I	Future scenarios
104	(Henriksson <i>et al.</i> 2017b)	Whiteleg shrimp	Ponds	Indonesia	M	I	Future scenarios
105	(Henriksson <i>et al.</i> 2017b)	Tiger shrimp	Ponds	Indonesia	P	E	Future scenarios
106	(Iribarren <i>et al.</i> 2010a)	Mussels	Rafts	Spain	M	E	Sectorial approach
107	(Iribarren <i>et al.</i> 2010b)	Mussels	Rafts	Spain	M	E	Sold Canned
108	(Iribarren <i>et al.</i> 2010b)	Mussels	Rafts	Spain	M	E	Sold Fresh
109	(Iribarren <i>et al.</i> 2010c)	Mussels	Rafts	Spain	M	E	Sold Frozen
110	(Iribarren <i>et al.</i> 2010c)	Mussels	Rafts	Spain	M	E	Sectorial approach
111	(Iribarren <i>et al.</i> 2010c)	Mussels	Rafts	Spain	M	E	Sold Canned
112	(Iribarren <i>et al.</i> 2010c)	Mussels	Rafts	Spain	M	E	Sold Fresh
113	(Iribarren <i>et al.</i> 2012b)	Turbot	All (sectorial approach)	Spain	M	I	Feed oriented
114	(Iribarren <i>et al.</i> 2012a)	Turbot	All (sectorial approach)	Spain	M	I	With probiotics
115	(Iribarren <i>et al.</i> 2012a)	Turbot	All (sectorial approach)	Spain	M	I	Without probiotics
116	(Jerbi <i>et al.</i> 2012)	Seabass	FTS	Tunisia	M	I	Cascade raceway

117	(Jerbi <i>et al.</i> 2012)	Seabass	FTS	Tunisia	M	I	Traditional raceway
118	(Jonell and Henriksson 2015)	Giant tiger shrimps	Integrated with mangrove	Vietnam	P (IAA)	E	Non-organic certification
119	(Jonell and Henriksson 2015)	Giant tiger shrimps	Integrated with mangrove	Vietnam	P (IAA)	E	Organic certification
120	(Kluts <i>et al.</i> 2012)	Striped catfish	Integrated with rice	Vietnam	P (IAA)	SI	Comparison of technologies
121	(Kluts <i>et al.</i> 2012)	tilapia, kissing gourami, giant gourami, silver barb, common carp, silver carp, and striped catfish	Integrated with rice	Vietnam	P (IAA)	SI	Comparison of technologies
122	(Kluts <i>et al.</i> 2012)	Striped catfish	Ponds	Vietnam	M	I	Comparison of technologies
123	(Lourguioui <i>et al.</i> 2017)	Mussels	Suspended culture	Algeria	M	I	Current situation scenario
124	(Lourguioui <i>et al.</i> 2017)	Mussels	Suspended culture	Algeria	M	I	Concurrent scenario
125	(Lourguioui <i>et al.</i> 2017)	Mussels	Suspended culture	Algeria	M	I	Cooperative scenario
126	(Lozano <i>et al.</i> 2010)	Mussels	Rafts	Spain	M	E	Identification of inefficient sites via DEA
127	(McGrath <i>et al.</i> 2015)	Chinook salmon	FTS	Canada	M	I	New technology assessment
128	(Medeiros <i>et al.</i> 2017)	Tambaqui	Ponds	Brazil	M	I	Comparison of mono and polyculture
129	(Medeiros <i>et al.</i> 2017)	Amazon shrimps	Ponds	Brazil	M	I	Comparison of mono and polyculture
130	(Medeiros <i>et al.</i> 2017)	Tambaqui and shrimps	Ponds	Brazil	P	I	Comparison of mono and polyculture
131	(Medeiros <i>et al.</i> 2017)	Tambaqui and shrimps	Ponds	Brazil	P	I	Comparison of mono and polyculture
132	(Mungkung <i>et al.</i> 2006)	Shrimps	NA	Thailand	M	I	Technology hotspots
133	(Mungkung <i>et al.</i> 2013)	Tilapia and carp	Net cages	Indonesia	P	SI	Large farms, high fish stocking density
134	(Mungkung <i>et al.</i> 2013)	Tilapia and carp	Net cages	Indonesia	P	SI	Small farms, low fish stocking density
135	(Nhu <i>et al.</i> 2016)	Pangasius catfish	Ponds	Vietnam	M	I	Aquaculture stewardship certification
136	(Nhu <i>et al.</i> 2016)	Pangasius catfish	Ponds	Vietnam	M	I	No Aquaculture stewardship certification
137	(Pahri <i>et al.</i> 2016)	Cockles	Rafts	Malaysia	M	E	Technology hotspots
138	(Papatriphon <i>et al.</i> 2004b)	Rainbow trout (large)	FTS	France	M	I	Comparison of species
139	(Papatriphon <i>et al.</i> 2004b)	Rainbow trout (pan-size)	FTS	France	M	I	Comparison of species
140	(Papatriphon <i>et al.</i> 2004b)	Rainbow trout (very large)	FTS	France	M	I	Comparison of species
141	(Pelletier and Tyedmers 2010)	Tilapia	Net cages	Indonesia	M	I	Cradle-to-destination (Chicago)
142	(Pelletier and Tyedmers 2010)	Tilapia	Net cages	Indonesia	M	I	Cradle-to-destination (Rotterdam)
143	(Pelletier and Tyedmers 2010)	Tilapia	Net cages	Indonesia	M	I	Cradle-to-packaging
144	(Pelletier and Tyedmers 2010)	Tilapia	Net cages	Indonesia	M	I	Cradle-to-farm gate
145	(Pelletier and Tyedmers 2010)	Tilapia	Ponds	Indonesia	M	I	Cradle-to-farm gate

146	(Pelletier <i>et al.</i> 2009)	Atlantic salmon	All (country approach)	Norway	All	All	Country comparison
147	(Pelletier <i>et al.</i> 2009)	Atlantic salmon	All (country approach)	United Kingdom	All	All	Country comparison
148	(Pelletier <i>et al.</i> 2009)	Atlantic salmon	All (country approach)	Chile	All	All	Country comparison
149	(Pelletier <i>et al.</i> 2009)	Atlantic salmon	All (country approach)	Canada	All	All	Country comparison
150	(Pelletier <i>et al.</i> 2009)	Atlantic salmon	All (country approach)	Global	All	All	Country comparison
151	(Phong <i>et al.</i> 2011)	Striped catfish, tilapia, gourami, barb and carp	Ponds integrated with orchard or rice	China	P (IAA)	I	Technology hotspots
152	(Samuel-Fitwi <i>et al.</i> 2013b)	Rainbow trout	FTS	Germany	M	I	Comparison of technologies
153	(Samuel-Fitwi <i>et al.</i> 2013b)	Rainbow trout	FTS	Germany	M	E	Comparison of technologies
154	(Samuel-Fitwi <i>et al.</i> 2013b)	Rainbow trout	RAS	Denmark	M	I	Comparison of technologies
155	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Area expansion in China
156	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Area expansion in Germany
157	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Area expansion in Denmark
158	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Increase intensity in China
159	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Increase intensity in Germany
160	(Samuel-Fitwi <i>et al.</i> 2013c)	Rainbow trout	NA	Germany	M	I	Increase intensity in Denmark
161	(Santos <i>et al.</i> 2015)	Giant shrimps	Ponds	Brazil	M	SI	Better effluent management
162	(Santos <i>et al.</i> 2015)	Amazon shrimps	Ponds	Brazil	M	SI	Better effluent management
163	(Santos <i>et al.</i> 2015)	Giant shrimps	Ponds	Brazil	M	SI	Conventional management
164	(Santos <i>et al.</i> 2015)	Amazon shrimps	Ponds	Brazil	M	SI	Conventional management
165	(Seves <i>et al.</i> 2016)	All fishes sold on the Netherlands	All (country approach)	The Netherlands	All	All	Country assessment
166	(Smáráson <i>et al.</i> 2017)	Arctic char	Ponds	Iceland	M	I	Feed oriented
167	(Wilfart <i>et al.</i> 2013)	Carp, tench, roach, perch, sander and pike	Ponds	France	P	E	Comparison of technologies
168	(Wilfart <i>et al.</i> 2013)	Atlantic salmon	NA ^{††}	France	M	I	Comparison of technologies
169	(Wilfart <i>et al.</i> 2013)	Carp, tench, roach, perch and pike	Ponds	France	P	SI	Comparison of technologies
170	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Fresh fillet, Cradle-to-destination Paris
171	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Fresh, gutted head-on, Cradle-to-destination Moscow

172	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Fresh, gutted head-on, Cradle-to-destination Oslo
173	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Fresh, gutted head-on, Cradle-to-destination Paris
174	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Fresh, gutted head-on, Cradle-to-destination Tokyo
175	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Frozen fillet, Cradle-to-destination Paris
176	(Winther <i>et al.</i> 2009)	Salmon	All (country approach)	Norway	All	All	Frozen, gutted head-on, Cradle-to-destination Shanghai
177	(Winther <i>et al.</i> 2009)	Blue mussels	All (country approach)	Norway	All	All	Country approach
178	(Yacout <i>et al.</i> 2016)	Tilapia	Ponds	Egypt	M	I	Comparison of intensities
179	(Yacout <i>et al.</i> 2016)	Tilapia	Ponds	Egypt	M	SI	Comparison of intensities

†: RAS=Recirculating aquaculture system; FTS=Flow-through system.

‡: IAA=Integrated agriculture-aquaculture; AP=Aquaponics.

§: I=Intensive; SI=Semi-intensive; E=Extensive.

¶: FCR=Feed conversion ratio

††: Reported as RAS but inconsistencies were found between this information and the results of the assessment.

Table S3: List of the feed scenarios analyzed in that literature review. NR=Not relevant.

ID	Study	Species	Aquafeed type	Country
1	(Boissy <i>et al.</i> 2011)	Rainbow trout	Low fish meal feed	France
2	(Boissy <i>et al.</i> 2011)	Atlantic salmon	Low fish oil feed	Scotland
3	(Boissy <i>et al.</i> 2011)	Rainbow trout	Standard feed	France
4	(Boissy <i>et al.</i> 2011)	Atlantic salmon	Standard feed	Scotland
5	(Cashion <i>et al.</i> 2016)	Atlantic salmon	Conventional feed	Norway
6	(Cashion <i>et al.</i> 2017)	NR	Fish meal	Global
7	(Cashion <i>et al.</i> 2017)	NR	Fish oil	Global
8	(Fréon <i>et al.</i> 2017)	NR	Conventional feed produced in factory using heavy fuel	Peru
9	(Fréon <i>et al.</i> 2017)	NR	Conventional feed produced in factory using gas	Peru
10	(Fréon <i>et al.</i> 2017)	NR	Prime fishmeal produced in modern factory	Peru
11	(Fréon <i>et al.</i> 2017)	NR	Feed produced in residual plant	Peru
12	(Iribarren <i>et al.</i> 2012b)	Turbot	Continental aquafeed	Spain
13	(Iribarren <i>et al.</i> 2012b)	Turbot	Marine aquafeed	Spain
14	(Papatryphon <i>et al.</i> 2004a)	Rainbow trout	Norwegian and Peruvian fish meal	France
15	(Papatryphon <i>et al.</i> 2004a)	Rainbow trout	Peruvian fish meal + by product of fishery in France	France
16	(Papatryphon <i>et al.</i> 2004a)	Rainbow trout	Low content of fish meal, high content of plants	France
17	(Papatryphon <i>et al.</i> 2004a)	Rainbow trout	No fish meal, only plants	France
18	(Parker and Tyedmers 2012)	NR	Fish meal for aquaculture, from Atlantic krill	Norway
19	(Parker and Tyedmers 2012)	NR	Fish oil for aquaculture, from Atlantic krill	Norway
20	(Pelletier and Tyedmers 2007)	Salmon	Conventional feed	Canada
21	(Pelletier and Tyedmers 2007)	Salmon	Conventional feed with organic ingredients and by-products instead of FMFO	Canada
22	(Pelletier and Tyedmers 2007)	Salmon	Conventional feed with organic ingredients	Canada
23	(Pelletier and Tyedmers 2007)	Salmon	Low FMFO feed with organic ingredients	Canada
24	(Pelletier and Tyedmers 2010)	Tilapia	Conventional feed	Indonesia
25	(Samuel-Fitwi <i>et al.</i> 2013a)	Rainbow trout	Rapeseed meal based feed	Germany
26	(Samuel-Fitwi <i>et al.</i> 2013a)	Rainbow trout	Soybean meal based feed	Germany
27	(Samuel-Fitwi <i>et al.</i> 2013a)	Rainbow trout	Conventional feed	Germany
28	(Seghetta <i>et al.</i> 2017)	NR	Feed from <i>Saccharina latissima</i> dried (macro algae) type 1	Denmark

29	(Seghetta <i>et al.</i> 2017)	NR	Feed from <i>Laminaria digitata</i> dried (macro algae) type 2	Denmark
30	(Smáráson <i>et al.</i> 2017)	Arctic char	Black soldier fly larvae based feed	Iceland
31	(Smáráson <i>et al.</i> 2017)	Arctic char	Conventional feed	Iceland
32	(Smáráson <i>et al.</i> 2017)	Arctic char	Low FM feed	Iceland
33	(Strazza <i>et al.</i> 2015)	NR	Conventional feed produced in Norway	Norway
34	(Strazza <i>et al.</i> 2015)	NR	Conventional feed produced in the UK	United Kingdom
35	(Strazza <i>et al.</i> 2015)	NR	Food waste from cruise	Global
36	(Taelman <i>et al.</i> 2013)	NR	Pilot study of <i>Nannochloropsis sp.</i> with big upscaling of the factory (micro algae)	Spain
37	(Taelman <i>et al.</i> 2013)	NR	Pilot study of <i>Nannochloropsis sp.</i> (micro algae)	Belgium
38	(Taelman <i>et al.</i> 2013)	NR	Pilot study of <i>Nannochloropsis sp.</i> With small upscaling of the factory (micro algae)	Belgium

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PAPER IIA

LCA of aquaculture systems: methodological issues and potential improvements

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LCA of aquaculture systems: methodological issues and potential improvements

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Abstract

Purpose The aquaculture sector is the fastest growing food production industry. Life-cycle assessment (LCA) can be a useful tool to assess its environmental impacts and ensure environmentally sustainable development. Years ago, critical reviews of LCA methodology have been conducted in that field to evaluate methodological practice. However, how effective were these reviews in improving LCA application? Are there any remaining issues that LCA practitioners should address in their practice?

Methods We tackle the above questions by critically reviewing all LCA cases applied to aquaculture and aquafeed production systems from a methodological point of view. A total of 65 studies were retrieved, thus tripling the scope of previous reviews. The studies were analysed following the main phases of the LCA methodology as described in the ISO standards, and the authors' choices were extracted to identify potential trends in the LCA practice.

Results and discussion We identified five main methodological issues, which still pose challenges to LCA practitioners: (i) the functional unit not always reflecting the actual function of the system, (ii) the system boundary often being too restricted, (iii) the multi-functionality of processes too often being handled with economic allocation while more recommendable ways exist, (iv) the impact coverage not covering all environmental impacts relevant to aquaculture and (v) the interpretation phase usually lacking critical discussion of the methodological limitations. We analysed these aspects in depth, highlighting trends and tendencies.

Conclusions For each of the five remaining issues, we provided recommendations to be integrated by practitioners in their future LCA practice. We also developed a brief research agenda to address the future needs of LCA in the aquaculture sector. The first need is that emphasis should be put on the construction of aquaculture life-cycle inventory databases with a special need for developing countries and for post-farming processes. Additionally, method developers should develop and/or refine characterisation models for missing impact pathways to better cover all relevant impacts of seafood farming.

Keywords Aquafeed · Fish · Life-cycle assessment · Food production · LCA methodology · Review · Seafood

1 Introduction

Because of a growing global population, food demand currently faces a significant increase, which is expected to intensify in the future (UN 2017). As a main diet component in many

countries and a healthy source of protein, seafood demand is no exception to that trend. Historically, fisheries were the main source of producing seafood, but with a majority of the fish stocks now fished at maximum capacity or at unsustainable levels, seafood production has progressively transitioned to aquaculture, for which production has boomed over the last decades (FAO 2016). However, the aquaculture industry remains associated with a number of impacts on the environment, such as climate change, aquatic eutrophication or loss of biodiversity due to escapes of farmed animals (Naylor et al. 2000; Diana 2009; Ottinger et al. 2016). It is therefore crucial to ensure that the fast development of the aquaculture sector happens in the most sustainable way possible.

A common tool to assess environmental sustainability of products or systems is life-cycle assessment (LCA; ISO 2006a, b). It has already been widely applied to assess

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aquaculture systems since the early 2000s. The number of LCA studies published in scientific literature has intensified in the last few years now reaching over 50 publications (Fig. 1; Bohnes et al. 2018). Previous critical reviews have been made, looking at the findings of the LCA studies as well as the methodological choices of LCA practitioners (Henriksson et al. 2012; Parker 2012; Aubin 2013; Cao et al. 2013; Pahri et al. 2015). For instance, Henriksson et al. (2012) analysed methodological practices from 12 LCA studies of aquaculture systems. The authors concluded on a lack of transparency in the data used, and reported a limited coverage in the number of impacts assessed by the studies and too narrowly scoped system boundaries, for which they provided a number of recommendations to future studies. The aforementioned past reviews have provided similar messages to improve LCA practice based on other limited sets of studies (see Fig. 1). However, now that the number of publications has more than quadrupled, how have these messages been taken up by LCA practitioners in the aquaculture sector? For example, has system boundary completeness and environmental impact coverage been improved in recent LCA studies conducted since critical reviews were published?

Here, we conducted a follow-up critical review of all existing LCA studies in the aquaculture sector to address how LCA practice has evolved since previous reviews and recommendations were released and identify potential points that still remain to be addressed by practitioners. In the subsequent sections, we use this review basis to (i) critically evaluate the methodological choices of LCA studies in the aquaculture sector and provide a new set of recommendations wherever needed (Sect. 3) and (ii) outline a research agenda to address the requirements for more consistent LCA practice in the aquaculture sector (Sect. 4).

2 Material and methods

2.1 Identification of the studies

To enter the scope of this review, LCA studies had to comply with the following requirements: (i) assessing at least one production system of aquaculture or aquafeed (i.e. feed for aquatic organisms farmed in aquaculture); (ii) focusing on seafood production for direct human consumption; and (iii) including at least two impact categories (therefore, we excluded, e.g. stand-alone carbon footprinting studies). Only articles in peer-reviewed journals and publicly available peer-reviewed LCA reports published up to June 2017 and written in English were considered. The studies were found using Web of Science online database (<http://webofknowledge.com>) and Google Scholar research tool (<https://scholar.google.dk/>), with the keywords “Life-cycle assessment” + “Aquaculture”, “Life-cycle analysis” + “aquaculture”, “LCA” + “aquaculture”, “Life-cycle assessment” + “aquafeed” and “Life-cycle assessment” + “aquaculture” + “feed”. Additional studies were identified by

Fig. 1 Number of LCA studies conducted on aquaculture systems per year since 2004 (extracted from Bohnes et al. 2018), and number of these LCA studies included in previous critical reviews (Henriksson et al. 2012; Parker 2012; Aubin 2013; Cao et al. 2013; Pahri et al. 2015)

cross-referencing existing reviews in that field (Henriksson et al. 2012; Parker 2012; Aubin 2013; Cao et al. 2013; Clark and Tilman 2017). For further details on the identification and selection of the studies, the readers are referred to Bohnes et al. (2018), who used the same pool of LCA studies to analyse trends and patterns of environmental impacts from different aquaculture systems.

2.2 Review criteria

Studies were analysed following the main phases of the LCA methodology as described by the ISO standards (ISO 2006a, b), i.e. goal definition, scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and life-cycle interpretation. Table 1 presents the list of the main methodological choices retrieved. Data quality was categorised as poor, medium or good following the same criteria than Laurent et al. (2014). They were then compiled and analysed to identify potential trends and patterns in practice, and their relevance was critically considered in the context of the ISO14040-4 standards (ISO 2006a, b). Based on this analysis and the recommendations made in previous reviews of LCA methodology (Henriksson et al. 2012; Parker 2012; Aubin 2013), we identified and prioritised five important methodological issues. These mainly relate to the scope

Table 1 List of the methodological choices retrieved from the reviewed LCA studies

Category	Information extracted from the studies
General information	Mention of the ISO standards; objectives of the studies.
Goal definition	Intended use of the study; decision context.
Scope definition	Object of the study; functional unit; Life-cycle inventory framework modelling; multi-functional processes handling method; elements entering and excluded from the system boundary; scale of the study (e.g. number of farms, country studied etc.); impact coverage.
Life-cycle inventory	List of data sources; data quality (Laurent et al. 2014); existence of a critical discussion regarding data representativeness; software used for modelling.
Life-cycle impact assessment	Life-cycle impact assessment methodologies used; normalisation (if applicable); weighting (if applicable).
Interpretation	Existence of a sensitivity analysis; elements tested in the sensitivity analysis (if applicable); existence of a quantitative uncertainty analysis.

definition of the study (one also addresses interpretation of the results), which is an essential phase to ensure consistency and reliability in the LCA results. Using ISO standards, we then established a set of recommendations to LCA practitioners to potentially improve the quality of future LCA studies.

3 Past LCA practices and improvement potentials

We retrieved and reviewed a total of 65 LCA studies on aquaculture and aquafeed systems; 51 of them assessed aquaculture production systems, 10 assessed aquafeed production systems and 4 included the assessment of both types of systems. An exhaustive list of all the LCA studies included in the review is available in Table 2 for the studies assessing aquaculture production and Table 3 for the ones assessing aquafeed production.

3.1 Making the functional unit reflect the *actual function* of aquaculture systems

More than 70% of the LCA practitioners assessing aquaculture systems have adopted a functional unit (FU) based on a mass of live-weight seafood (see Fig. 2a; Table 2). This particularly high proportion reflects the focus of many LCA studies on the production side, assessing a function based on the needs and benefits of the producer. It contrasts with the few authors (e.g. Avadí and Fréon 2015) that selected a mass of edible or processed product, hence basing their reference on the consumer needs, which convey a consumption approach. With regard to the 14 studies that assessed aquafeed production systems, 11 of them adopted a FU based on mass of aquafeed, while the remaining ones followed a different approach and used a mass of protein (Strazza et al. 2015), a surface of cultivation (Seghetta et al. 2017) or an energy content (Taelman et al. 2013)—see Fig. 2a; Table 3. It should be highlighted that 14% of the studies had not explicitly defined and reported a FU, which thus had

to be deduced from the text and tables/figures of the articles. This lack of transparency only slightly decreased since the last review of LCA methodologies, from 16% in the studies prior to 2013 to 12% in the more recent studies.

The FU is particularly important for comparative assessments because of the need to quantify an identical function for both systems to allow a fair comparison. Defining differently the FUs may lead to different ranking of the assessed solutions, as illustrated by Avadí et al. (2015), who tested two different FUs based on either the mass of live-weight product or the mass of edible product. Furthermore, when assessing the life-cycle of a food product, using a FU based on the product total mass does not reflect the actual function of that product, i.e. to provide nutritional benefits to the consumer (Sala et al. 2017; Sonesson et al. 2017). Most past critical reviews in the field already pointed out practitioners' preference to define a mass-based FU. They highlighted that the lack of consensus on the way to define the FU reduces the possibility of comparison between studies (Aubin 2013; Cao et al. 2013) and stressed the risk that the choice of the FU might change the results of the study (Henriksson et al. 2012; Parker 2012).

To ensure consistency, it is therefore recommended to define the FU of aquaculture LCA studies based on nutritional criteria of the product, such as protein or energy content, as already emphasised by Sala et al. (2017) and Sonesson et al. (2017). A consensus should be reached in the LCA food community to determine which nutritional criteria the defined FU should rely on as a function of the goal of the LCA, so that future studies can align with this same basis and become more comparable. Such recommendation also applies to aquafeed systems. Indeed, the primary function of the aquafeed is to feed the fishes, that function is only captured properly when a nutritional reference is used. For instance, comparing plant-based ingredients with fish-based ingredients based on a mass alone, as done in several past studies (see Table 3), might be highly misleading, because the amount required to fulfil the needs of the fish is highly different for the two ingredients. To prevent such situation, we

Table 2 LCA studies assessing aquaculture production systems with their main methodological choices (total of 55 studies; not available (N.A.); inspired from Bohnes et al. 2018)

Reference	Species	Technology ^a	FU basis ^b	System boundary ^c	MFPH ^d	Impact categories ^e			Other indicators	
						Non-toxic	Toxic	Energy	NPPU	WD
Abdou et al. (2017a)	Seabass/seabream	Net-cages	LW	CtF	A (bio m)	x		x	x	
Abdou et al. (2017b)	Multiple (polyculture)	Cages	LW	CtF	N.A.	x		x	x	
Aubin et al. (2006)	Turbot	RAS	LW ^f	CtF	N.A.	x		x	x	
Aubin et al. (2009)	Trout/turbot/seabass	FTS/RAS/net-cages	LW	CtF	N.A.	x		x	x	x
Aubin and Fontaine (2014)	Mussels	Bouchots	PP	CtF + pr + pa	N.A.	x		x		x
Aubin et al. (2015)	Multiple (polyculture)	Ponds	LW	CtF + t	A (ge; e)	x		x	x	
Avadi and Fréon (2015)	Pacu/trout/tilapia	Ponds/floating cages	E	CtF + t + d	A (m)	x	x	x	x	
Avadi et al. (2015)	Pacu/trout/tilapia	Ponds/floating cages	LW + E	CtF	A (ge)	x	x	x	x	
Ayer and Tyedmers (2009)	Salmon/char	RAS/FTS/net-pens/floating bags	LW	CtF	SE; A (ge)	x		x		
Ayer et al. (2016)	Salmon	Net-pens	LW	CtF	A (ge)	x		x		
Baruthio et al. (2008)	Multiple (polyculture)	Ponds	LW	CtF	A (e)	x		x		
Besson et al. (2016)	Catfish	RAS	LW	CtF	A (e)	x		x		
Boissy et al. (2011)	Salmon, trout	FTS/Net-cages	LW ^f	CtF	A (e)	x	x	x	x	x
Bosma et al. (2011)	Catfish	Ponds	LW	CtF	A (m)	x		x		
Boxman et al. (2016)	Tilapia	RAS (AP)	LW	CtF	SE	x		x		
Cao et al. (2011)	Shrimps	Ponds	LW + PP	CtF + pr + d	N.A.	x		x	x	
Chen et al. (2015)	Trout	FTS	LW	CtF	A (e)	x		x	x	x
Dekamin et al. (2015)	Trout	FTS/RAS	LW	CtF	N.A.	x		x	x	x
Roque d'Orbeastel et al. (2009)	Trout	FTS/RAS	LW	CtF	N.A.	x		x	x	x
Efole Ewoukem et al. (2012)	Multiple (polyculture)	Ponds, integrated	LW	CtF	A (e)	x		x	x	x
Ellingsen and Aanonsen (2006)	Salmon	N.A.	E	CtF + pr + t	A (m; e)	x	x			
Forchino et al. (2017)	Trout	RAS (AP)	Other	CtF	A (m)	x		x		
García García et al. (2016)	Seabream	Cages	LW	CtF	A (m)	x		x		
Grönroos et al. (2006)	Trout	Net-cages/floating cages/ponds	LW	CtF + pr + pa	N.A.	x				
Henriksson et al. (2015)	Shrimps/catfish/tilapia	Various	PP	CtF + d	A (m; e)	x	x			
Henriksson et al. (2017a)	Tilapia	Ponds	LW	CtF	A (m; e)	x				
Henriksson et al. (2017b)	Various (country production)	Ponds/Cages	LW	CtF	A (e)	x		x		
Iribarren et al. (2010a)	Mussels	Rafts	PP + other	CtF + EoL	SE	x	x			
Iribarren et al. (2010b)	Mussels	Rafts	PP	CtF + pr + pa + EoL	A (m)	x	x	x		
Iribarren et al. (2010c)	Mussels	Rafts	Other	CtF + pr + pa + EoL	SE	x	x			
Iribarren et al. (2012b)	Turbot	Sectorial approach	PP	CtF + c	N.A.	x				
Iribarren et al. (2012a)	Turbot	Sectorial approach	LW	CtF	N.A.	x				
Jerbi et al. (2012)	Seabass	FTS	LW	CtF	N.A.	x		x	x	x
Jonell and Henriksson (2015)	Shrimps/catfish	Mangrove, integrated	LW	CtF	A (e)	x				

Table 2 (continued)

Reference	Species	Technology ^a	FU basis ^b	System boundary ^c	MFPH ^d	Impact categories ^e			Other indicators	
						Non-toxic	Toxic	Energy	NPPU	WD
Kluts et al. (2012)	Catfish/multiple (polyculture)	Rice, integrated	LW	CtF	SE; A (m)	x	x			
Lourguoui et al. (2017)	Mussels	Rafts	LW	CtF	N.A.	x		x		
Lozano et al. (2010)	Mussels	Rafts	LW	CtF	N.A.	x				
McGrath et al. (2015)	Salmon	FTS	LW ^f	CtF	A (nut)	x		x	x	
Medeiros et al. (2017)	Multiple (polyculture)	Ponds	LW	CtF	SE	x		x	x	x
Mungkung et al. (2006)	Shrimps	N.A.	PP	CtF + pr + t + d + c	N.A.	x	x			
Mungkung et al. (2013)	Multiple (polyculture)	Cages	LW	CtF	A (e)	x		x	x	x
Nhu et al. (2016)	Catfish	Ponds	LW	CtF	A (ex)	x		x		
Pahri et al. (2016)	Cockles	Rafts	PP	CtF + pr + pa	N.A.	x	x			
Papatryphon et al. (2004b)	Trout	FTS	LW	CtF	A (e)	x		x	x	
Pelletier et al. (2009)	Salmon	Net-pens	LW ^f	CtF	A (ge)	x		x	x	
Pelletier and Tyedmers (2010)	Tilapia	Net-pens/ponds	LW + PP	CtF + pr + pa + d	A (ge)	x		x	x	
Phong et al. (2011)	Multiple (polyculture)	Ponds	LW	CtF	A (e)	x		x		
Samuel-Fitwi et al. (2013b)	Trout	RAS/FTS	LW	CtF	SE	x				
Samuel-Fitwi et al. (2013c)	Trout	N.A.	LW	CtF	SE	x				
Santos et al. (2015)	Shrimps	Ponds	LW	CtF + t + d	A (e)	x		x	x	x
Seves et al. (2016)	Various (country approach)	Various (country approach)	LW ^f	CtF	N.A.	x				
Smáráson et al. (2017)	Char	Ponds	LW	CtF	A (m)	x	x			
Wilfart et al. (2013)	Multiple (polyculture)/Salmon	Ponds/RAS	LW	CtF	A (e)	x		x	x	x
Winther et al. (2009)	Salmon/Mussels	Various (country approach)	PP	CtF + pr + t	A (m)	x		x		
Yacout et al. (2016)	Tilapia	Ponds	LW ^f	CtF	A (ge)	x		x		

RAS, recirculating aquaculture system; FTS, flow-through system; AP, aquaponics; LW, live weight; PP, processed and packaged product; EW, edible weight; CtF, cradle-to-farm gate; pr, processing; pa, packaging; t, transport; d, distribution; EoL, end-of-life; c, consumption; A, allocation; m, mass; ge, gross energy; e, economic; nut, nutritional; ex, exerg; SE, system expansion; NPPU, net primary production use; WD, water dependence

^a Main technologies

^b Basis of definition of the functional units (FU)

^c System boundary parts included in the study

^d Multi-functional process handling (MFPH)

^e Non-toxic impact categories include climate change, aquatic eutrophication, stratospheric ozone depletion, acidification, tropospheric ozone formation and particulate matter formation; toxic impact categories include human toxicity and ecotoxicity

^f No explicitly stated FU

Table 3 LCA studies assessing aquafeed production systems with their main methodological choices (total of 14 studies)

Reference	Type of aquafeed	Species	FU basis	MFPH ^a	Impact categories ^b			Other indicators	
					Non-toxic	Toxic	Energy	NPPU	WD
Boissy et al. (2011)	Low FMFO aquafeed	Salmon/trout	Mass ^c	A (e)	x	x	x	x	x
Cashion et al. (2016)	Conventional aquafeed	Salmon	Mass	A (ge)				x	
Cashion et al. (2017)	FMFO	Not differentiated	Mass ^c	A (ge)	x			x	
Fréon et al. (2017)	Conventional aquafeed, prime fishmeal; different factories	Not differentiated	Mass	A (ge)	x	x	x		
Iribarren et al. (2012b)	Continental vs. marine aquafeed	Turbot	Mass	N.A.	x				
Papatriphou et al. (2004a)	Different level of FMFO in aquafeed	Trout	Mass	A (e)	x		x	x	
Parker and Tyedmers (2012)	FMFO	Not differentiated	Mass ^c	A (ge; m)	x		x	x	
Pelletier and Tyedmers (2007)	Low FMFO aquafeed; organic aquafeed	Salmon	Mass ^c	A (ge)	x	x	x	x	
Pelletier and Tyedmers (2010)	Conventional feed	Tilapia	Mass	A (ge)	x		x	x	
Samuel-Fitwi et al. (2013a)	No FMFO aquafeed	Trout	Mass	SE	x				
Seghetta et al. (2017)	Macro algae-based aquafeed	Not differentiated	Surface of cultivation	SE	x	x	x		
Smáráson et al. (2017)	Low FMFO aquafeed; black soldier fly larvae-based feed	Char	Mass	A (m)	x	x	x		
Strazza et al. (2015)	Food waste	Not differentiated	Proteins mass	A (m)	x	x			
Taelman et al. (2013)	Micro algae-based aquafeed	Not differentiated	Exergy	N.A.	x	x			

FMFO, fishmeal/fish oil; FU, functional unit; A, allocation; m, mass; ge, gross energy; e, economic; ex, exergy; SE, system expansion; NPPU, net primary production use; WD, water dependence

^a Multi-functional process handling (MFPH)

^b Non-toxic impact categories include climate change, aquatic eutrophication, stratospheric ozone depletion, acidification, tropospheric ozone formation and particulate matter formation; toxic impact categories include human toxicity and ecotoxicity

^c No explicitly stated FU

Fig. 2 Distributions of the 65 reviewed LCA studies (a) between the different types of functional units (FU) for aquaculture and aquafeed, (b) between the different methods for handling multi-functionality, and (c) between covered impact categories in the assessments

recommend to compare full diets to ensure comparability of the aquafeeds' function.

3.2 Including all relevant life-cycle stages of aquaculture production

Several processes constitute the life-cycle stages of an aquaculture production system. As illustrated in Fig. 3, they can be divided as feed production, energy supply, chemical inputs, infrastructures and equipment, seafood production, processing, packaging, distribution, consumption and seafood end-of-life. All these elements need to be included in an LCA to ensure a *complete* life-cycle. However, 69% of the studies reviewed herein did not consider the last five aforementioned processes and ended their assessments at farm gate, conducting therefore “cradle-to-farm-gate” LCAs. Additionally, the production and use of chemicals and the infrastructures and equipment were often neglected, with only 64% of the studies including the first and 60% considering the latter. The reason stated by the authors for not including these stages are the expected negligible impacts these may have or the lack of primary data and available databases to support a consistent modelling.

Including all elements that may have important environmental impacts is necessary to conduct a comprehensive LCA and avoid burden shifting from one environmental impact to another

(Hellweg and Milà i Canals 2014; Ziegler et al. 2016). Some post-farming processes have been demonstrated to be of potentially great importance on the final impact scores and can increase impacts (e.g. transport to distribution; Seves et al. 2016) or decrease them (e.g. reuse or recycling at end-of-life; Iribarren et al. 2010a). Parker (2012) already introduced the benefits of a larger system boundary than cradle-to-farm gate. Additionally, by conducting a detailed contribution analysis (i.e. hotspot analysis) from the documented results, Bohnes et al. (2018) found out that 78 and 84% of the existing studies that adopted a complete life-cycle reported a non-negligible contribution of 5% or more for the production and use of chemicals and for the infrastructures and equipment, respectively. Henriksson et al. (2012) had already highlighted the need of a broadly encompassing system boundary and the importance of including infrastructures. We reiterate this still ignored recommendation to consider a *complete* life-cycle when performing LCAs of aquaculture systems, using the processes in Fig. 3 as guidance to ensure a comprehensive assessment of the environmental impacts.

3.3 Using system expansion instead of allocation for handling multi-functional processes

It is common in LCA that a single process produces multiple outputs or functions, called therefore a multi-functional

Fig. 3 Different stages and processes of aquaculture production and types of system boundaries (adapted from Bohnes et al. 2018). The thick arrows represent the stages between which transport can occur (dependent on case study)

process. Usually, only one of the functions needs to be included in the assessment, hence the necessity of methodologies to solve process multi-functionality. From the retrieved studies, 58% of them selected allocation, 13% system expansion, and 3% used both, while 26% of the studies did not explicitly state which method they used—see Fig. 2b. A difference is witnessed between the studies published until 2012 and the more recent ones: the use of system expansion increased from 7 to 16%, and the proportion of studies not stating which method they used dropped from 36 to 19%. The use of allocation did not change considerably. As evidenced in the sensitivity analyses of numerous LCA studies included in the current review (e.g. Winther et al. 2009; Kluts et al. 2012; Wilfart et al. 2013; Aubin et al. 2015; Jonell and Henriksson 2015; McGrath et al. 2015; Nhu et al. 2016; Medeiros et al. 2017), the choice of method to solve process multi-functionality is of great importance for the LCA results.

Past general reviews already noted the lack of consensus regarding the approach to be used for handling multi-functionality and, without providing explicit recommendations, they highlighted the need for a better argumentation to justify the choice of the approach applied (Henriksson et al. 2012; Parker 2012; Aubin

2013). According to ISO 14044, it is recommended to prioritise sub-division of the system whenever possible (ISO 2006b). However, the cases when this approach is possible are rare, and the second most recommended method is then system expansion, and, if that is not possible, the LCA practitioner should apply allocation and prioritise physical allocation keys over other types such as, e.g. economic allocation (ISO 2006b).

Considering that more than half of the studies applied allocation, it is therefore legitimate to question whether or not system expansion is applicable in aquaculture systems. By analysing the studies that applied system expansion, it appears that this method can be applied in handling the outputs of several co-products related to aquaculture systems. Natural fertilisers can thus fulfil the same function as synthetic fertilisers (see, e.g. Ayer and Tyedmers 2009; Kluts et al. 2012), seafood or agricultural co-products are equivalent to the same products from conventional production ways, usually from monoculture (e.g. Boxman et al. 2016; Medeiros et al. 2017), aquafeed co-products can be functionally equivalent to the marginal corresponding ingredients (see, e.g. Samuel-Fitwi et al. 2013a), and waste products can generally be valorised, e.g. mussels shells used to produce calcium, thus

replacing conventional means (Iribarren et al. 2010a). The above examples cover most of the secondary functions arising from aquaculture and aquafeed production systems and demonstrate that using system expansion is possible in that area for most multi-functional processes.

However, some LCA practitioners have argued that some of the multi-functionality cited above are not solvable by using system expansion. We observed that usually this comes from a difference in the definition of the function to isolate. For instance, the production of fish meal always has fish oil as a co-product, and some LCA practitioners would isolate the fish oil production by expanding the system and include the production of other oils, e.g. vegetal ones, whereas other authors would argue that this is not reasonable because of the different nutritional compositions that make fish oil unique, hence the use of allocation. This is a legitimate decision of the LCA practitioner, but it is not always well justified in the articles under review and allocation often seems to be the default solution. Therefore, we recommend to explain in more details the reason why allocation cannot be avoided and to state explicitly the function considered, which has no alternative processes. Once allocation have been selected, Fig. 2b shows that a third of the LCA studies chose an economic allocation key over a physical one, which should be considered as a last resort according to the ISO hierarchy to solve process multi-functionality (see above: ISO 2006a, b). Indeed, economic allocation keys are not stable because of market fluctuations, which leads to constantly changing LCA results (Ayer et al. 2007). In most cases when system expansion cannot be applied, the multi-functionality concerns the production phase and therefore physical allocation such as energy content or mass allocation can be used instead of economic criteria. This was already recommended by Ayer et al. (2007) in their critical review of co-product allocation in fisheries and aquaculture, where they argued that gross-energy allocation is the most scientifically accurate solution for the cases when system expansion is not applicable.

We therefore recommend that LCA practitioners follow more rigorously the hierarchy specified in the ISO standards to handle multi-functionality of processes. In particular, system expansion should be more prioritised over allocation as it is often applicable. Practitioners are thus encouraged to check previous LCA studies that used system expansion (see above examples) and when allocation cannot be avoided, to use physical allocation keys instead of economic ones.

3.4 Covering all environmental impacts of aquaculture

Figure 2c shows that a majority of studies included climate change, aquatic eutrophication, acidification and cumulative energy demand (all four categories covered in more than 50% of studies), but that all other impact categories are rarely

included. Only a few studies included toxicity impacts (25% for human toxicity and 28% for ecotoxicity) or land use (38%), and less than half included net primary production use (NPPU) and water dependence, two impact categories specific and of high relevance to food production systems (Aubin et al. 2009; Cashion et al. 2016). Overall, the spectrum of included impact categories was limited, their selection was poorly justified and exclusively based on the argument that previous LCA studies on aquaculture systems had similarly limited impact coverage. Rare were the authors, who justified the selection of their impact assessment on scientific foundations about the potential relevance of different impact categories (see as example of good practice Avadí and Fréon 2015).

In their critical reviews, Henriksson et al. (2012) and Aubin (2013) already highlighted the limited impact coverage of LCA studies on aquaculture. Together with the life-cycle perspective, the impact coverage is a key element in LCA to ensure a holistic dimension and reduce the risk of environmental burden-shifting (Laurent et al. 2012). When some categories for which the system has high environmental impacts are omitted, the results might be biased and the decisions based on the conclusions might lead to suboptimisation, i.e. decreasing some impacts while increasing others as relevant. For instance, toxicity impacts may be of high relevance in aquaculture systems, as showed by Kluts et al. (2012), who found a different ranking in their comparative study for freshwater ecotoxicity than for most of the other impact categories assessed. Other impacts are as relevant. The inclusion of land use impact category thus has been recommended by several authors (Bosma et al. 2011; Kluts et al. 2012; Samuel-Fitwi et al. 2013b; Dekamin et al. 2015; Jonell and Henriksson 2015), although it has until now mainly been assessed at an inventory level (i.e. total area of land occupied or transformed) without impact assessment. Additionally, indicators specific to biomass extraction that also account for the pressure exerted on wild fish stocks have been developed, and a number of approaches have been proposed although no consensus have yet been reached on a specific LCIA method (see, e.g. Lost Potential Yield (LPY) in Emanuelsson et al. 2014 or Biotic Natural Resource Depletion (BNRD) in Langlois et al. 2012). Therefore, we recommend the assessment of a broad variety of relevant impact categories in future LCA studies, including toxicity impacts and land use, as well as NPPU, water dependence and overfishing related impacts, which are not common to LCA applications, albeit relevant to aquaculture systems. LCIA methods for these categories exist and should be used, including, but not limited to, the USEtox model for toxicity impacts (Bijster et al. 2017), land use assessment method developed by Chaudhary et al. (2015) and recommended in Jolliet et al. (2018), the NPPU method described in Papatryphon et al. (2004a) and water dependence introduced and developed by Aubin et al. (2009).

3.5 Discussing the results with critical thinking and highlighting the limitations of the studies

Out of the 65 reviewed studies, an overall good quality of the data sources used in the studies was observed, with 85% of the studies relying on primary data and adequate literature sources with respect to data specificity and scope (see Sect. 2.2). However, only half of the studies critically discussed the representativeness of the data, which consists of data that are appropriate in terms of their geographical, temporal and technological aspects. To support the interpretation of LCA results, uncertainty and sensitivity analyses are recommended as part of the sensitivity check (ISO 2006a, b; Laurent et al. 2018). However, only 49% of the studies conducted a sensitivity analysis and 28% ran a quantitative uncertainty analysis.

The accuracy and hence the reliability of the LCA results are highly dependent on the quality of the data collected and the sensitivity and uncertainty underlying in the model. Therefore, these matters need to be critically analysed in the interpretation phase of the assessment during the completeness, consistency and sensitivity checks to support the conclusions from the results as well as the recommendations based on them. The review conducted by Henriksson et al. (2012) emphasised a lack of sensitivity analyses in the LCA studies, and the results of the current study also showed a lack of critical analysis, regardless of the time of publication of the studies (problem encountered in recent studies too). This prevents the reader from putting the results in perspective and assessing the robustness of the results.

Therefore, we recommend future LCA practitioners to critically discuss their LCI and include a detailed description of the limitations of study in the interpretation. We also recommend to systematically perform a sensitivity analysis of a large selection of criteria covering the input data and the modelling choices, and to conduct a quantitative uncertainty analysis such as a Monte Carlo simulations (available in most LCA software), wherever possible, to complement a default qualitative analysis. Guidance for performing interpretation of LCA results is available in Laurent et al. (2018).

4 Research needs in LCA for aquaculture

From the critical review of 65 LCA studies, we additionally identified two main research needs that should be addressed to improve LCA applications to the aquaculture sector: constructing comprehensive LCI data sets and developing missing relevant impact pathways. Both are developed in the following subsections.

4.1 Increasing the pool of LCI data sets for aquaculture

Several studies reported a lack of available LCI for modelling processes within the life-cycle of aquaculture systems, hence preventing them from including these elements in their assessments. Data regarding all post-farming stages (e.g. transport, processing, distribution, consumption and end-of-life) are thus extremely scarce, if not inexistent, as highlighted previously by Abdou et al. (2017a). For primary data collection, LCA practitioners are usually in contact with the seafood farmers, who often know little about the processes occurring to their seafood after farm gate. Therefore, the processing, packaging, transport and distribution steps are almost always missing from the assessment because of the lack of information, which might have an important impact on the final results. For instance, Winther et al. (2009) found that transport can be a main contributor to the final scores depending on the distribution zone of the product, and Iribarren et al. (2010b) highlighted the importance that processing and packaging may have on the results. Specific processes of aquaculture are also poorly documented. Infrastructures for instance are problematic because some parts, such as the water filtration systems, are difficult to model by the LCA practitioners due their high complexity in term of number of components and variety of materials.

Additionally, there is a general lack of databases concerning developing countries, leading to only a few LCA studies performed in these regions and to less robust assessments when some have been attempted (Dekamin et al. 2015; Bohnes et al. 2018). This is especially problematic in aquaculture assessments as more than 95% of the world production of seafood from aquaculture takes place in Asia, where only few general LCI are publicly available (Bohnes et al. 2018). In the Ecoinvent database (Weidema et al. 2013), which is the most widely used LCI database in our review (used in 74% of the studies), only few processes are specific to, e.g. Indonesia (35 processes), Vietnam (14 processes) or the Philippines (17 processes), which are the 2nd, 4th and 5th most important aquaculture producers in the world, respectively (FAO 2016).

We therefore encourage all aquaculture stakeholders to share data for enabling the construction of LCI data sets, which would improve the overall quality of future LCA studies and facilitate their applications to relevant systems and locations.

4.2 Missing impact pathways

Several studies have pointed out that the current LCIA methodologies do not cover all the environmental impacts relevant to aquaculture, as highlighted by Ellingsen and Aanonsen (2006), Samuel-Fitwi et al. (2013b), Aubin et al. (2015), Avadi and Fréon (2015), Henriksson et al. (2015, 2017a),

Nhu et al. (2016) and Abdou et al. (2017a). Below, two major gaps are highlighted: impacts from escapes and damages related to use of antibiotics and medicine treatment.

The impacts of escapes on the local environments are thus not addressed, albeit being a well-documented issue in that sector (Naylor et al. 2000; Diana 2009). If the escaped species are invasive, they can affect the balance of the local ecosystem because of the introduction of new predators, which can have important consequences as the extinction of local species (Arisemendi et al. 2009; Peeler et al. 2011). If the farmed species are already present in the local ecosystems, it can be as problematic because of breeding that changes the genetics of farmed specimens and make them different from the wild ones, thus altering the natural balance of species present in the ecosystem and potentially contributing to biodiversity losses and/or changes in ecosystem functioning (Youngson and Saroglia 2001; Naylor et al. 2005). Some authors already highlighted the need of including that issue in life-cycle impact assessment and proposed ways of accounting for it (Ford et al. 2012). However, no actual impact pathways have been developed yet, and escapes are only suggested to be considered at inventory level (i.e. accounting the number of fish that escaped per year; Ford et al. 2012).

Another uncovered impact pathway is the effect of antibiotics and other medicine used in seafood farms, and their subsequent impacts on human health through, for example antimicrobial resistance. Indeed, the use of antibiotics in food production as growth promoter or medical treatment leads to the development of resistant microorganisms, which will not be treatable by that antibiotic anymore, thereby inducing higher rates of infections by that microorganism in the human population (Cabello et al. 2013). This has recently been highlighted by the World Health Organisation, which recommended addressing this topic urgently (WHO 2018). The use of antibiotics should also be included in the modelling of impact pathways for ecotoxicity because of the potential impacts of these products on natural ecosystems. Antibiotics are designed to affect microorganisms in general and are therefore a threat for bacteria but also fungi and microalgae (Kümmerer 2009). Similarly, the impacts of cleaning products used during the farming stage are not included in some toxicity impact methodologies because these products are usually inorganics and their environmental fate is not always well known. For instance, the USEtox model, which covers 27 inorganics (mainly metals) and 3077 organic substances (Huijbregts et al. 2015a, b), does not include some of the common bleach such as sodium hypochlorite, thus calling for extending the substance coverage in its characterisation factor database.

For the two above methodological gaps, we recommend new method developments in LCIA to complement existing impact pathways and develop characterisation model to integrate these new cause-effect chains.

5 Conclusions

Based on the review of 65 LCA studies in the aquaculture sector, five major issues were identified and analysed. For each of them, recommendations were provided aiming to improve the quality and reproducibility of future LCAs in that sector. In summary, LCA practitioners should (i) choose a functional unit based on nutritional qualities, (ii) prefer system expansion over allocation and seek inspiration and assistance in published studies that applied this rule, (iii) assess a life-cycle as complete as possible in line with the goal of the study, (iv) include an environmental impact coverage as broad as possible and (v) pay special attention to the consistency/completeness check and the sensitivity and uncertainty analysis during the interpretation of the results. Drawing on these, we also identified two key research needs that method developers in LCI and LCIA should undertake, namely expanding LCI database with aquaculture-specific processes and characterising missing impact pathways, respectively. It is also worth noting that as highlighted in Sects. 3.1 to 3.5, a lack of transparency in the methodological choices is latent in many studies, with a non-negligible proportion of them not even stating their choices and assumptions. These not only refer to old studies, i.e. prior to previous critical reviews but also to a number of recent studies. Such poor practice is a great impediment to the credibility and reuse of the LCA results for large-scale analysis or comparative assessments.

We therefore recommend to future practitioners that they undertake these above messages. A few of our recommendations are not new and have already been indicated in previous critical reviews, be it within the field of aquaculture or in other fields. Recent studies have however showed that these key recommendations are not implemented by LCA practitioners. This demonstrates that there is a need for LCA practitioners to better inform themselves on the conduct of LCA in their specific fields of applications, e.g. by reading critical reviews, to integrate consistent guidance and overcome methodological challenges in their cases. Peer reviewers of scientific articles should also be aware of these critical reviews and of the methodological issues indicated therein to prevent studies with insufficient documentation and/or inconsistencies—as some identified in the current review—from being published. Such practice should eventually contribute to bring more consistency and reliability in LCA studies to support decision- and policy-making processes in fields as important and relevant as the aquaculture sector.

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PAPER IIb

Methodological choices of LCA applied to aquaculture systems: Critical review & recommendations

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Abstract

Aquaculture has been the fastest growing food production sector for several decades. Despite its reputation of being a sustainable protein source, this industry has been associated with several environmental impacts, such as climate change or aquatic eutrophication. It is therefore important to ensure that its fast development occurs with as low environmental impacts as possible. Life cycle assessment (LCA) is the most common tool to assess environmental sustainability of systems and processes, and has been extensively applied on aquaculture systems. In this work, we reviewed 65 LCA studies applied on aquaculture and aquafeed systems, and analyzed the methodological practice of LCA by the practitioners. We selected four important issues that highly influence the final scores of the LCA studies: the functional unit, the handling of multifunctionality, the system boundary and the impact coverage. For each of them, a thorough analysis was conducted, leading to a set of recommendations that we believe will improve the quality, reproducibility and comprehensiveness of future LCA studies in the aquaculture field.

Keywords: *aquaculture; seafood; fish; LCA methodology; critical review.*

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1. Introduction

Seafood is a main diet component in many countries (Hosomi et al., 2012). Until recently, its production came predominantly from fisheries. However, as a majority of fish stocks are currently fished at full or exceeded capacities, seafood production is increasingly turning to aquaculture (FAO, 2016). Seafood farming has been reported to lead to several potential impacts on the environment and human health, such as eutrophication of surrounding water bodies, climate change, water consumption or land transformation (Diana, 2009; Naylor et al., 2000). It is therefore important to ensure that the booming aquaculture development takes place in an environmentally-sustainable way.

In that context, life cycle assessment (LCA) has been widely applied to aquaculture production systems over the last decade. However, how has the LCA methodology been applied? Which methodological choices did the authors take, and to what extent were they appropriate to answer their research questions? To answer these questions, a critical literature review, new in its coverage of studies was conducted, with the objectives to analyze the relevance of methodological choices in relation to the research goals of the studies, and establish a set of recommendations for LCA practitioners to improve the quality and comparability of future studies.

2. Material and methods

Only peer-reviewed scientific literature written in English was considered in the study. All articles and public reports conducting an LCA on at least one aquaculture or aquafeed production system entered the scope of the review. The life cycle impact assessment (LCIA) phase needed to include at least two impact categories for inclusion of a given study. For more details regarding the selection and identification of the studies, the reader is referred to Bohnes et al. (2018a,b). The studies were evaluated using as reference the ISO requirements and ILCD technical guidance on LCA application (EC, 2010; ISO, 2006). In this paper, we specifically elaborate on four key aspects that were identified as challenging for practitioners: the functional unit (FU), the handling of process multifunctionality, the delimitation of system boundaries and the impact coverage. They are among the methodological choices that divide the most the LCA studies under review while being of high importance for the results.

3. Results and discussion

The review included 65 studies, 51 of them assessing aquaculture production systems, 10 of them assessing aquafeed production systems, and 4 assessing both. In comparison, previous critical reviews on LCA methodology encompassed a maximum of 20 studies on aquaculture and aquafeed (Aubin, 2013; Henriksson et al., 2012; Parker, 2012). Details and references of these 65 studies are documented in Bohnes et al. (2018a,b).

3.1. Functional unit

Approximately two third of the reviewed LCA studies defined their functional units based on a live-weight mass of product, whereas the last third defined it based on an edible mass of product, a processed and packaged mass of product or a nutritional criteria. This reflects that most authors adopted a production point of view, where the function of the system is defined based on the producer needs and benefits, in opposition to a consumption perspective, where the function is built on the consumer needs. However, most of the studies position their research goals around food security and the need of producing seafood for direct human consumption, thus calling for a FU relying on nutritional criteria rather than on mass basis. We therefore recommend practitioners to adopt the latter approach to defining their FU in future studies.

3.2. Multi-functionality handling

As illustrated in Figure 1, more than half of the LCAs applied allocation, and for many of them with an economic allocation key. However, the ISO 14044:2006 hierarchy (ISO, 2006) states that system expansion should be used in priority, and only when it cannot, allocation should be applied. If allocation cannot be avoided, physical criteria should be preferred to economic ones (ISO, 2006).

Figure 1: Handling of multifunctional processes in LCA studies of aquaculture (total of 65 studies)

About 16% of the studies under review applied system expansion on all or on at least some cases of multifunctional processes, thus evidencing that this LCI modelling approach can be used to solve various multi-functionality of aquaculture systems such as polyculture, the use of manure as natural fertilizer, the

co-products of aquafeed, or the valorization of seafood waste. Additionally, it is worth noticing that a quarter of the studies did not specify how they handled multi-functional processes (Figure 1). The above findings therefore call for LCA practitioners to be more transparent and compliant with the ISO standards.

3.3. System boundaries

Most past studies conducted a “cradle-to-farm-gate” assessment, considering only the life cycle stages up to the farming of the seafood, and neglecting processing, packaging, transport, distribution, consumption and end-of-life. The studies, which considered these stages, however generally found that they had important contributions to the final scores (e.g. Winther et al., 2009). Additionally, a great majority of studies excluded chemical use and production, and infrastructures and equipment, while these are typically found to be a non-negligible (e.g. Medeiros et al., 2017). Complete system boundaries, with a categorization of the different system components, as recommended in Bohnes et al. (2018b), should therefore be followed to ensure no suboptimisation or burden-shifting from one system component to another.

3.4. Impact coverage

Table 1 reports that most studies included climate change, eutrophication, acidification and energy use, but neglected all other impact categories. In particular, toxicity-related impacts or water use impacts were included in only ca. 25% of the studies, albeit being of great relevance for aquaculture (Pahri et al., 2015). Some impact pathways specific to food production or aquaculture production systems – net primary production use and water dependence – have been developed but are not assessed in all LCA studies of aquaculture (Papatryphon et al., 2004; Aubin et al., 2009). Practitioners should therefore include a broader impact coverage in future studies, including all the above mentioned impact categories.

Additionally, a number of relevant impacts of aquaculture are not covered in the current LCIA methodologies, and should therefore be developed. This is the case of methods for assessing impacts of antimicrobial resistance on human health or damage to biodiversity from invasive or genetically-modified species (Diana, 2009; WHO, 2018). LCIA methods for these pathways require to be developed

Table 1: Main impact categories assessed in LCA of aquaculture systems (total of 65 studies; NPPU=Net primary production use; BRU=Biotic resource use).

Impact category	Number of studies assessing that impact category	Percentage of studies assessing that impact category
Climate change	64	98%
Aquatic eutrophication	59	91%
Acidification	52	80%
Cumulative energy demand	45	69%
Land use	25	38%
Ecotoxicity (marine and/or freshwater)	18	28%
Human toxicity	16	25%
Additional common LCA categories	17	26%
NPPU or BRU	25	38%
Water dependence	12	18%

4. Conclusion and recommendations

Out of the 65 LCA studies reviewed, important inconsistencies were observed, despite the fact that a number of points had been addressed in previous critical reviews, thus calling for more rigor in the application of LCA to aquaculture systems. Building on the aforementioned observations, we provide the following overarching recommendations to LCA practitioners in their future studies on aquaculture production systems:

- Define a FU based on nutritional criteria in order to reflect the consumption perspective relevant to most studies.
- Assess the complete life-cycle of the production system, i.e. not limiting the system boundary to the farm-gate, and including chemicals use and production as well as infrastructures and equipment.
- Follow the ISO 14044:2006 hierarchy for handling multifunctionality of processes in the systems, with (i) prioritizing system expansion over allocation and physical over economic allocation when it cannot be avoided, and (ii) reporting transparently and with justifications which modelling approach was selected.
- Assess a broad variety of impact categories, including toxicity impacts, land use impacts, net primary production use and water dependence, which have been largely overlooked in past studies.

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PAPER III

Are aquaculture growth policies in high-income countries due diligence or illusionary dreams? Foreseeing policy implications on seafood production in Singapore

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Are aquaculture growth policies in high-income countries due diligence or illusionary dreams? Foreseeing policy implications on seafood production in Singapore

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ABSTRACT

In the beginning of 2019, the Singaporean government announced its desire to increase domestic food production and, in particular, aquaculture to reach 30% of self-sufficiency by 2030. Similar policies aiming at encouraging aquaculture growth abound in high-income countries in recent years, but have had limited success. Hence, this paper investigates the potential implications of such policies to foresee consequences beforehand and improve the policy's chances of success. Three scenarios of aquaculture development are built for Singapore until 2040, among which a business-as-usual scenario and two explorative scenarios aiming at increasing aquaculture production, the first emphasizing existing technologies and the second giving priority to novel and innovative ones, like recirculating aquaculture systems. These scenarios are assessed using an adapted version of the supply-demand partial equilibrium model Asiafish to challenge their viability in the socioeconomic context of Singapore. Only the two explorative scenarios are found to allow the Singaporean government to reach its goal in terms of seafood self-sufficiency by 2030, one of which appears to have strong advantages. In this scenario, imports decrease by 28% by 2040, seafood self-sufficiency reaches 69% and 90% of all aquaculture originates from innovative technologies, which would make Singapore an aquaculture tech-hub. It also has higher benefits within Singapore environmental, social and economic constraints such as land and aquafeed scarcity.

KEYWORDS

Aquaculture production; Singapore; seafood self-sufficiency; Asiafish model; scenarios; supply-demand.

1 INTRODUCTION

With a growing world population combined with higher average incomes, global food demand is drastically increasing, and, in particular, the demand for seafood is rising (FAO, 2018a). Seafood is a key ingredient in current and future diets, not only because of its recognized health benefits, but also because of its high potential of production growth (Ahmed and Lorica, 2002; Golden et al., 2017; HLPE, 2014; McManus et al., 2009; Williams et al., 2000). Indeed, fish and other seafood can come from either capture or aquaculture, and while capture fisheries have limited development potential because of the majority of the fish stocks being already fully exploited, overexploited, depleted or recovering, aquaculture is expected to remain the fastest growing food production sector in the coming decades (FAO, 2018b, 2016). Due to this promising potential, encouraging and supporting aquaculture development has been a priority for governments of countries all over the world.

Over the years, multiple countries have introduced governmental plans and policies attempting to develop aquaculture production in different ways and at different levels. Some of them focused on starting or increasing production of specific species or implementing new technologies, while other policies aimed to initiate or boost an entire aquaculture industry, which was until then marginal or inexistent. Such strategic plans were outlined in low-income as well as high-income countries, motivated mainly by food security in the former category of countries, and by increasing economic activity in remote areas, self-sufficiency and the need for healthier diets in the latter (HLPE, 2014; Röcklinsberg, 2014). All these plans and policies, however, aimed at increasing the overall aquaculture production in a country or region. In the European Union, for example, each country has been encouraged by the European Commission to produce a multiannual national plan, in which it details its aquaculture development strategy, with an emphasis on sustainability (COM, 2013).

However, despite being associated with the highest growth rate of all food production industries, aquaculture has increased drastically in only few places and countries and has had a slow growth in high-income countries in general (Abate et al., 2016; Anderson et al., 2019; Costa-Pierce, 2010; FAO, 2016). Leaving aside noteworthy exceptions such as Norway, most aquaculture policies implemented in high-income countries have failed in the past years, with their growth objectives ending up not being met. The most notable example is the European Union, where aquaculture production has decreased by 8% between 2000 and 2016 despite substantial subsidies aimed at increasing production (Guillen et al., 2019). The case of shellfish in Canada is also remarkable, as both the federal and the provincial governments launched numerous policies and initiatives to increase production which was expected to be multiplied ten-fold within the following 10 years, but it only doubled during this period (Howlett and Rayner, 2004). The outcomes of these policies can be problematic, as in some cases poor governance can result in conflicts

over marine sites, disease outbreaks and public mistrust over aquaculture products (Hishamunda et al., 2014). Furthermore, several authors have pointed out the limited consideration of relevant stakeholders during the elaboration of these policies, also termed the “people-policy gap” (Ertör and Ortega-Cerdà, 2017; Krause et al., 2015). And, other studies have blamed the lack of science-based assessment and the limited knowledge of the environmental implications of these policies, or the “science-policy gap” (Dürrenberger et al., 1999). Finally, a recent study by Anderson et al. (2019) argued that economists have had limited involvement in aquaculture policy design and evaluation, which has influenced the industry growth in most countries. Overall, a too weak evaluation of the far-reaching implications of aquaculture policies seems to be an important element in the failure of these policies, and therefore, it appears essential to assess and anticipate the consequences of such policies on socioeconomic factors and the environment beforehand.

In high-income countries, one of the main causes to aquaculture policy failure is the misalignment between government targets in terms of production and the actual potential of aquaculture development based on existing environmental regulations, economic incentives and public perception of the industry (Abate et al., 2016; Kaiser and Stead, 2002). Food security is often not a direct motivation to increase food production in these countries, which makes the aforementioned obstacles difficult to overcome. Nonetheless, anticipating potential trends in aquaculture growth by accounting for economic, social and environmental factors is necessary to define more realistic aquaculture policies for developed countries in the future.

Indeed, despite the past failures, new aquaculture development plans are still emerging in various high-income countries, trying to trigger their “blue revolution” (Eikeset et al., 2018). Singapore, for example, announced a new ambitious plan for aquaculture development at the beginning of 2019 (Zulkifli, 2019; Mahmud, 2019). Currently, Singapore has a limited seafood production and thus imports more than 90% of its domestic consumption (SFA, 2019b). In their new policy, Singapore introduced an objective of 30% of seafood self-sufficiency by 2030, which would imply a several fold multiplication of the domestic production within the coming 10 years (i.e. the “30-by-30” policy - Zulkifli, 2019; Mahmud, 2019). This remains low compared to the self-sufficiency targets set by other Southeast Asian countries, including those in the past (e.g. self-sufficiency of 60% for rice in Brunei by 2035, 90% for rice in Malaysia by 2010 or 100% for sugar and beef in Indonesia by 2019 - OECD/FAO, 2017), but Singapore unique geographical situation and limited land availability restrains the direct comparison with its neighbors. Considering the tendency of past aquaculture policies to be unsuccessful and the level of change this new policy implies in such a short period, the risk of failure appears high and it seems therefore particularly important to foresee the various potential consequences of an increasing seafood production in Singapore to allow the aquaculture sector to successfully reach the objectives presented by the government. Thereby, motivated by the importance of such assessment in this particular case, the purpose of this paper is to determine how

to anticipate the consequences of the “30-by-30” policy on the Singaporean food system and produce recommendations that might help preventing the policy failure.

In the context of foreseeing general implications of policy, economic demand-supply partial equilibrium models are typically used to assess the complex dynamic interactions between consumption, production and trade. The AsiaFish model, for example, has been used to assess the aquaculture growth potential of nine Asian countries, including the Philippines, China and Indonesia (WorldFish, 2009). The studies based on these national models demonstrated the value of such approach and its usefulness in the assessment of aquaculture policies (Dey et al., 2008, 2005b; Rodriguez et al., 2005; Tran et al., 2017). However, such applications have focused on low-to-middle income countries or already important seafood producers rather than high-income countries, such as Singapore, for which their use could help mitigate the risk of policy failure as observed in the past.

Indeed, even though its neighbors are all significant aquaculture producers (e.g. Indonesia, Malaysia, and Thailand), Singapore presents a unique profile and thus is not influenced by the successful aquaculture story of the rest of Southeast Asia. First, incomes are much higher in the city-country, which has one of the highest GDP per capita in the world (World Bank, 2019). Furthermore, it has limited land resources and no local production of cheap aquafeed, which also increases the costs of production. All these arguments suggest that if Singapore wants to boost its aquaculture production it would not use the same technologies as other countries with similar climate. Just like for other industries, it is likely that Singaporean farmers will prioritize investment in new and advanced technologies, less intensive in resources (such as land) and feeds thanks to highly optimized processes. However, determining which technologies and species would help Singapore in fulfilling its objective of strengthening self-sufficiency is not straightforward. Hence, different scenarios reflecting different options of technology development should be considered and assessed.

Against this background and to answer our research question, this paper investigates the potential implications of Singapore’s new aquaculture policy using a multi-market equilibrium model to provide an overview of the economic consequences while considering environmental and societal constraints. To that end, we (1) build realistic scenarios of aquaculture development until 2040, taking into account specific socioeconomic and ecological barriers in the local industry, (2) adapt the commonly used Asiafish model to assess these different scenarios with a supply-demand dynamic approach, differentiating the potential technologies and promising species for Singapore, and finally (3) analyze the policy implications and their viability in the context of a developed nation with barely no history in aquaculture production. First, Singapore seafood production and related policies situation are portrayed in Section 2. Then, the Asiafish model and its adapted version are explained in Section 3, emphasizing the differences relative to the original

model, followed by the description of the input data and the design of the developed scenarios in Section 4. Section 5 presents the analysis of the results before we discuss the policy implications for Singapore as well as limitations of the model and the present analysis in Section 6.

2 SINGAPOREAN SEAFOOD PRODUCTION AND ASSOCIATED POLICIES

In 2018, out of the 113 assessed countries in the world, Singapore scored the highest in the Global Food Security Index, a measurement tool that addresses the issues of affordability, availability, quality and safety of food in a country (The Economist Group, 2018). However, the same report identified that Singapore food security index is also one of the most sensitive to climate and natural resource risks. Indeed, Singapore is highly reliant on imports with regard to food supply due to its limited domestic production. Domestic production covers approximately 10% of the total food consumption and 9% of seafood consumption (SFA, 2019b). This makes the country vulnerable to trade and supply chain disruption, as supplier countries might decide to e.g. reduce exports for their own food security in the case of a drop in production (The Economist Group, 2018). This is already happening, and for example, for the past 5 years, the Malaysian government has prohibited the export of several species of fish and shrimp around Chinese New Year to avoid shortage in local markets due to the combination of reduced production because of the monsoon and high demand in the festive season (Koh, 2018).

Hence, Singapore's authorities have recently announced the introduction of strong new policies to "enhance food security" and allow the country to rely less on imports. These policies will rely on three main strategies: "Diversify import sources", "Grow overseas" and "Grow local" (Zulkifli, 2019). The latter comes with a challenging goal of producing 30% of Singapore's food consumption by 2030 within Singapore, or the "30 by 30" plan, and seafood production will not be excluded from this growth (Zulkifli, 2019; Mahmud, 2019). In this way, the Singaporean government wants to increase its food self-sufficiency in order to strengthen its high but vulnerable food security. Using the self-sufficiency ratio (SSR) defined by the FAO (2012) for fresh seafood (FS), the governmental target can be quantified as follows:

$$SSR_{FS} [\%] = \frac{production\ FS}{production\ FS + imports\ FS - exports\ FS} * 100 = \frac{production\ FS}{total\ domestic\ demand\ FS} * 100 \geq 30\% \quad (Eq. 1)$$

Self-sufficiency in terms of processed fish is not considered in the study because it is not possible to differentiate whether processed seafood is produced using domestic fish or imported fish.

Currently, capture fishery is a small industry producing mainly marine fishes and crustaceans (annual production of 746 and 269 tons in 2017, respectively; FAOSTAT, 2019b), and is not expected to increase in the future (SFA, 2019a). Concerning aquaculture, approximately 120 Singaporean fish farms existed in

2018, producing mainly high-value species, such as barramundi, milkfish or Golden pompano (FISHSTAT, 2019a). A total of 5370 tons of seafood were produced from aquaculture in 2017 in Singapore, among which 4514 tons were marine fishes (FAOSTAT, 2019a). Fingerlings are mainly imported, although there are few hatcheries in the country.

With 720 km² and around 5.6 million inhabitants, Singapore is a relatively small but populated island (SINGSTAT, 2019). For the last decades, land has been prioritized for other activities than agriculture and aquaculture by the authorities. In addition, labor is expensive in the city-country, especially compared to its closest neighbors (e.g. Indonesia), which makes labor-intensive activities such as agriculture non-competitive. As a result, Singapore will have difficulties producing seafood while being competitive. It is therefore likely that the country will decide to prioritize investments in innovative and state-of-the-art (SOTA) aquaculture technologies. Such investment would also contribute to the image of the city-country as a major seafood tech hub and be aligned with the Singaporean Economic Development Board statements about the country being the “Asian technology capital” (SFA, 2019a; EDB, 2018). With this in mind, it is very likely that several new technologies will be introduced in Singapore aquaculture landscape, which will contribute to Singapore status as a seafood tech hub in Asia. As all technologies have different input requirements (i.e. land, feed or energy) it is therefore important to differentiate the new production by technological origin.

3 MODEL DESCRIPTION

The goal of this paper is to oversee and understand the potential implications of the recent Singaporean policy about seafood production and, in particular, to determine if the self-sufficiency objective is realistic in the current demand, supply and trade context of Singapore. For that, interactions between demand, supply and trade of seafood at country level need to be assessed. Few partial-equilibrium models and few general-equilibrium models have been developed to assess seafood production quantitatively. A review of the literature revealed that the most commonly used partial-equilibrium models are the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model and the AsiaFish model. The IMPACT model links economic, water and crop models and was developed by the International Food Policy Research Institute in the 90s to help decision-makers assess policies targeting hunger and poverty reductions (Robinson et al., 2015). This model was not selected for the current study because it is not publicly available, and its level of disaggregation of supply and demand products does not fit the requirements of this study (i.e. differentiating between technologies and grouping of species). An alternative model is AsiaFish, developed by the WorldFish Center in 2000, which was used as a starting point in the present study. This model focuses on seafood and fits the required level of disaggregation in

terms of species and technologies. It is a multi-product partial equilibrium model of fish supply, demand and trade with a possibility of high disaggregation in terms of markets, species and technologies (WorldFish, 2009). It was first developed to assess nine Asian countries, namely the Philippines, Thailand, China, Bangladesh, Sri Lanka, India, Indonesia, Vietnam and Malaysia, which has resulted in multiple studies on those countries (Dey, 2000; Dey et al., 2008, 2005b; Rodriguez et al., 2005; Tran et al., 2017). General-equilibrium models remain largely non-existent in analyzing the role of fish products and the interactions of fisheries and aquaculture with other sectors in the economy. Jacobsen *et al* (2016), however, remain the exception with a focus on analyzing interactions between agriculture and aquaculture when integrating nitrogen regulation of the two sectors.

Dey et al. (2005a) outlines the structure of the model and provides the theoretical basis for the model equations. AsiaFish is built around three key components: a consumer core, a producer core and a trade core (Dey et al., 2005a). The consumer core is a three-stage budgeting framework, which aims at describing households' behavior. The first stage separates food expenditure from non-food expenditure (Eq.2). The second stage isolates the demand for seafood as a whole from the rest of the food items (Eq.3). The third stage estimates the share of each fish category using a quadratic form of the Almost Ideal Demand System (AIDS) corrected with the stone price (Eq.4).

$$\log(FDEX) = \beta_0 + \beta_1 * \ln(PFD) + \beta_2 * \ln(PFDN) + \beta_3 * \ln(R) + \beta_4 * \ln(R)^2 \text{ (Eq.2)}$$

Where FDEX is the total food expenditure per capita, R the income per capita, PFD is the aggregate price of food items, PFDN is the aggregate price of non-food items, and β is the response parameters of the food expenditure function.

$$\log(FEX) = \theta_0 + \theta_1 * \ln(PF) + \sum_Z \theta_2 * \ln(PZ(Z)) + \theta_3 * \ln(FDEX) + \theta_4 * \ln(FDEX)^2 \text{ (Eq.3)}$$

Where FEX is the total expense of fish per capita, PF is the aggregate price of fish, PZ is the aggregate price of non-fish food items, and θ is the response parameters of the fish expenditure function.

$$SH(FD) = \gamma_0 + \sum_{FD} \gamma * \ln(PC(FD)) + \gamma_1 * \ln(FEX/stone) + \gamma_2 * \ln(FEX/stone)^2 \text{ (Eq.4)}$$

Where SH is the share of fish type FD in the total fish expenditure, PC is the price paid by the consumer for buying fish type FD in Singapore, γ are coefficients based on the demand and expenditures elasticities, and stone is the stone price index defined as following: $stone = \sum_{FD} SH(FD) * PC(FD)$. The Stone index measures the scale of consumption and the quadratic form of the last element in Eq. 4 appears when deducing the AIDS system from the minimization of expenditures subject to utility.

The producer core works around the notion of netput, which is defined as all inputs and outputs of the assessed systems. Each fish category, characterized by a species and a technology, corresponds to a set of associated netput. Some of them are outputs (i.e. seafood produced) and some other are inputs (i.e. labor, primary resources, feed, etc). A normalized quadratic profit function approach is used to estimate the quantities of netput supplied by the system and their corresponding price (Eq.5). These quantities will be positive for outputs and negative for inputs.

$$QA(n, y) = (\alpha_{n,0} + \alpha_n * PE(n, y)) * \lambda_{n,y} \text{ (Eq.5)}$$

Where n is a netput, QA is the total quantity supplied of netput n in year y , PE is the effective price of netput n in year y , $\lambda_{n,y}$ is the technological factor of netput n in year y , α_n are the elasticities of supply of netput n and $\alpha_{n,0}$ is a coefficient calibrated on the first year for netput n . The effective price PE represents the price of an effective quantity of netput provided by a given physical unit. It is directly linked to the efficiency and productivity of the system, hence qualified as effective in the technical sense. The effective price here is not associated with a specific physical unit but rather represents an increase in yield, illustrating general technological improvement. The ratio between the two in the AsiaFish model is given by the technological growth factors $\lambda_{n,y}$, also described by Dey et al. (2005a) as the proportional change of netput n due to technological progress or policy shift at year y compared to the starting year of the model, which is expressed in Eq.6:

$$PE_{n,y} = \lambda_{n,y} * PP_{n,y} \text{ (Eq.6)}$$

PP is the producer price. This directly influences the production of supply fish type i in year y because price and supply quantities are strongly linked through the other equations of the model, in a way that domestic production of fish type i in year y and $\lambda_{i,y}$ are proportional. In the current study, only outputs are considered, i.e. the production of seafood.

The trade core uses seafood export supply and import demand functions imposing the Armington assumption to estimate the quantities and prices of imports and exports. This assumption is common in applied general equilibrium models and it assumes that goods from different regions are imperfect substitutes that can have different prices in different countries (Armington, 1969). Therefore, the exported (imported) and domestic versions of a specific fish type are first combined in a foreign-domestic aggregate which is then considered the unique object of production (consumption) and whose composite price is $PARX$ ($PARM$) as in Equations 7 and 8.

$$PARX(FD) = \frac{PS(FD)*QH(FD)+PX(FD)*QX(FD)}{QSF(FD)} \text{ (Eq.7)}$$

$$PARM(FD) = \frac{PS(FD)*QHM(FD)+PM(FD)*QM(FD)}{QDF(FD)} \text{ (Eq.8)}$$

Where PARX (PARM) is the price of import-domestic (export-domestic) aggregate for fish type FD, PS is the supply price of fish type FD, QHX (QHM) is the domestic component of import-domestic (export-domestic) aggregate for fish type FD, PX (PM) is the imported (exported) price of fish type FD, QX (QM) is the exported (imported) quantity of fish type FD, and QSF (QDF) is the total quantity of supply (demand) for fish type FD.

A constant elasticity of transformation function is then used for the supply side and a constant elasticity of substitution function for the demand side. The exports (imports) are then obtained by optimization, constrained by the total supply (demand) and the foreign and domestic prices. Thus, the conditional supplies (demands) for the domestic component of exported (imported) fish are expressed in equations 9 and 10 (11 and 12).

$$QX(FD) = \delta_{2x}^{\sigma_{x,FD}} * \left(\frac{PX(FD)}{PARX(FD)} \right)^{\sigma_{x,FD}} * QSF(FD) \text{ (Eq.9)}$$

$$QHX(FD) = \delta_{1x}^{\sigma_{x,FD}} * \left(\frac{PS(FD)}{PARX(FD)} \right)^{\sigma_{x,FD}} * QSF(FD) \text{ (Eq.10)}$$

$$QM(FD) = \delta_{2m}^{\sigma_{m,FD}} * \left(\frac{PARM(FD)}{PM(FD)} \right)^{\sigma_{m,FD}} * QDF(FD) \text{ (Eq.11)}$$

$$QHM(FD) = \delta_{1m}^{\sigma_{m,FD}} * \left(\frac{PARM(FD)}{PS(FD)} \right)^{\sigma_{m,FD}} * QDF(FD) \text{ (Eq.12)}$$

Where δ_{1x} and δ_{2x} (δ_{1m} and δ_{2m}) are coefficients calibrated on the first year and $\sigma_{x,FD}$ ($\sigma_{m,FD}$) is the constant elasticity of substitution (transformation) or CES (CET) of fish type FD. The model is then solved by imposing the balance of supply and demand. The solution is obtained using the optimization software GAMS (Generalized Algebraic Modeling Solver) (GAMS Development Corporation 25.0.3, 2019).

To fulfill the objective of the analysis, it is necessary to disaggregate the domestic supply (i.e. production in the country) in categories separated by species, but also by technologies (i.e. fish 1 produced with technology A and fish 1 produced with technology B being two different supply categories). However, the consumer does not make a differentiation, at the demand level, between the same fish produced by different technologies (Carlucci et al., 2015). A more aggregated level of information is therefore needed in the demand core. The original model developed by the Worldfish center allows different levels of disaggregation for domestic supply and demand, but imports and exports are split using the highest level of disaggregation (whether it is the demand or supply – Figure 1a – Dey et al., 2005a). This means that in the original model, it is necessary to know what technology was used in the production of exported and

imported goods. These data are nearly impossible to find in practice; hence, we adapted the AsiaFish model to allow for more disaggregated domestic supply sources than demand sources while maintaining the lowest level of disaggregation of imports and exports level (i.e. the disaggregation of the demand sources – Figure 1b).

Figure 1: Structure of the original AsiaFish model (a) compared to the structure of the adapted model Asiafish (b). “Supply” corresponds to the domestic production, “Demand” to the domestic consumption and “Match” to trades.

These changes implied the addition of equations to link producer prices of species produced using different technologies. The production costs vary depending on the technology used, however, since the market for each fish type is integrated, the producer prices for the same fish type needs to be the same no matter the technology. The additional equations are generically formulated as in Eq. 13:

$$PP_{F1T1} = PP_{F1T2} \text{ (Eq. 13)}$$

Where PP_{F1T1} is the producer price of fish 1 produced with technology 1, PP_{F1T2} is the price of fish 1 with technology 2. Asiafish can then be solved recursively over time by assuming that values of exogenous variables and/or coefficients differ from one year to the next (such as population growth, inflation or technological factors). These projections are not forecasts, but illustrate demand and supply potential trends in the future (Dey et al., 2005a). Therefore, it is possible to generate scenarios modeling a change in policy over the years in the Asiafish model. In this paper, the desired change is reflected in a change of the technological growth factors (i.e. λ_{iy}). This corresponds to a proportional change in production (e.g. if 10% increase of fish 1 produced with technology 1 is requested on year y, then set $\lambda_{F1T1y} = 1.1 * \lambda_{F1T1y-1}$). The process can be iterative, especially when the target production is in a long-term future. The terms “increase/decrease of the technological growth factors (i.e. λ_{iy}) of x% for technology i” and “increase/decrease of production for technology i of x%” are used interchangeably in the rest of the paper.

This study follows the *ceteris paribus* assumption, and all parameters outside the system are assumed unchanged through the period considered. In particular, it is assumed that the other countries Singapore trade with do not have major changes in their seafood production during the timeframe.

4 INPUT DATA AND SCENARIOS

Based on official statistics and our communication with local farmers and authorities (FAOSTAT, 2019a,b; SFA, 2019a), we disaggregated the current Singaporean aquaculture into four species groups, namely marine fish species (e.g. milkfish, barramundi, Golden pompano), freshwater fish species (such as catfish and tilapia), mollusks (mainly green mussels), and crustaceans (mostly mud crabs), and the technologies currently used between low-tech and high-tech (Table 1). The difference between the two stems from the inputs required for the production (e.g. energy and infrastructure), the first one using basic technologies with low input requirements, and the second one using technologies that are more advanced and typically requiring more energy and infrastructure inputs. After an analysis of the literature about aquaculture in Southeast Asia and personal communication with the Singapore Food Authority (SFA), two SOTA technologies were additionally selected as likely to develop in Singapore in the coming years: recirculating aquaculture systems (RAS) and offshore aquaculture (SFA, 2019a). RAS corresponds to entirely closed and optimized systems where the water is treated and reused many times, hence reducing the nutrient emissions in natural water bodies and allowing highly optimized growth conditions. Offshore aquaculture consists of structures, usually sea cages, built substantially further from the shore than usual sea cages, in order to reduce the risks of disease spread between farms and to ensure a healthier environment for the fishes due to the more stable conditions of the offshore environment. Offshore sea cages need to be resistant to more extreme weather conditions than common sea cages, and therefore require deeper technological knowledge from the farmers. These two technologies are at an early development stage in most aquaculture countries, and are still uncommon in Southeast Asia. As such, their introduction in Singapore would contribute to making the country an aquaculture tech hub for this area of the world, and maybe even globally if the newest solutions are used. Table 1 combines the species groups grown in Singapore and the technologies with which they are currently or likely to be produced, and descriptions of all technologies used are available in Table 2. They correspond to the 10 supply categories that will be included in the Singaporean model.

Table 1: Singaporean seafood production categories with species and technologies (RAS = recirculating aquaculture system)

	Marine fishes	Freshwater fishes	Mollusks	Crustaceans
Capture	x			x
Aquaculture – low-tech (current)	x	x	x	
Aquaculture – high-tech (current)	x			x
Aquaculture – RAS (future)	x	x		
Aquaculture – offshore (future)	x			

Table 2: Description of the technologies currently used and likely to develop in Singapore aquaculture industry.

Implementation status	Technologies	Description
Current	Low-tech	<i>For marine fishes:</i> wooden structures floating on the sea growing the fishes in small nets at all growing stages, usually in the Straits of Johor. <i>For mollusks:</i> long lines close to the shore. <i>For freshwater fishes:</i> simple concrete ponds on land with flow-through water system.
Current	High-tech	<i>For marine fishes:</i> on-land recirculating water systems for the production of juveniles and large cages in the sea for the grow-out stage, usually in the south of the island. <i>For crustaceans:</i> optimized individual boxes with recirculating water systems.
Future	Recirculating aquaculture system (RAS)	Highly optimized processes where the water is treated and reused many times (can be used for the production of any type of seafood).
Future	Offshore aquaculture	Structures such as cages in the sea that are built far from the shore.

As explained in section 3.1, consumers are not influenced in their choice by the origin of products, and therefore the demand categories need to be differentiated only by group of species. Figure 2 presents the 10 different supply categories, differentiated by species and technology, and the corresponding 4 demand categories, differentiated by species only. Diadromous species are not commonly produced in Singapore, and therefore are not present as an entire category on the supply side. On the demand side, they are included in the category “marine fishes”.

Figure 2: Structure of the AsiaFish model adapted for Singapore, with the different supply, demand and matching categories, i.e. trade (RAS= recirculating aquaculture system).

To populate the model, data on seafood production and trade were retrieved from the Food and Agriculture Organization (FAO), while economic and demographic data for Singapore originated from the Singaporean Department of Statistics (FAOSTAT, 2017, 2019a, 2019b, 2019c; SINGSTAT, 2019). The reference year is 2017. Although it is available for inclusion in the model if relevant, algae, sharks, aquatic mammals, corals, cephalopods, frogs and ornamental fishes were disregarded from the study because of low or no domestic productions or because of their non-food purposes. Re-exports are removed from the balances using an average proportion of re-export of 61% (SINGSTAT, 2019). Domestic demand corresponding to local production of non-food products (mostly aquafeed) is considered negligible in Singapore, and for simplicity, it is not removed from the balances. The obtained seafood balance are as shown in Tables 3 and 4.

Table 3: Seafood balance for Singapore in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories.

	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
	Capture	Low tech	High tech	RAS	Offshore	Low tech	RAS	Low tech	Capture	Low tech	
<i>Production</i>	746	4,516	105	0	0	291	0	353	269	212	44,352
	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
<i>Consumption</i>	8,488					4,912		3,540	13,162		137,843
<i>Export</i>	1,196					191		16	42		14,922
<i>Import</i>	38,376					4,812		4,720	13,416		108,413
<i>Intermediate</i>	33,953					0		1,517	693		n.a.

Table 4: Seafood balance for Singapore in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 11 supply categories and the 5 demand categories.

	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
	Capture	Low tech	High tech	RAS	Offshore	Low tech	RAS	Low tech	Capture	Low tech	
<i>Production</i>	3,656	21,608	515	0	0	2,931	0	289	5,762	4,537	221,607
	Marine fishes					Freshwater fishes		Mollusks	Crustaceans		Processed seafood
<i>Consumption</i>	29,786					24,556		10,982	97,483		693,719
<i>Export</i>	5,927					588		272	676		88,439
<i>Import</i>	129,070					22,213		15,672	92,990		560,551
<i>Intermediate</i>	119,142					0		4,707	5,131		n.a.

With regard to demand, supply and expenditure elasticities differentiated by species' categories, a review of the literature revealed that such data did not exist for Singapore. Therefore, a generic Singaporean seafood elasticity was selected for the own-price demand and expenditure elasticities, with no differentiation between groups of species. No data have been found regarding cross-price elasticities between different groups of species, so the assumption is made that the seafood products between different groups of species are non-substitutable, non-complementary and all cross-price demand elasticities were set to zero. However, perfect substitution is assumed within each group of species. For the same reason, all the supply elasticities are set to zero based on the assumption that the quantities produced are either

independent from the price due to the intrinsic nature of the supply (case of fish capture) or more dependent on other factors than the price (for aquaculture). No inflation rate, exchange rate or other changes in prices are introduced in the model because of the high uncertainty associated with these parameters' evolution in the future, which would only introduce disturbance and complicate the interpretation of the results.

A detailed overview of the data required for the model for Singapore together with their respective sources is documented in Supplementary Methods, where one can also find a list of the main assumptions.

Based on the description of the intended policies about seafood production in Singapore (Section 2), three scenarios were developed: one business-as-usual scenario, following the past trends, and two explorative scenarios that assess different potential strategies of the Singaporean government based on their “30-by-30” policy. In the *Business-as-usual scenario (SG-BAU)*, Singapore remains an importer country. There is a moderate increase of 5% per year for the innovative technologies (RAS, offshore and high-tech) and no increase for low-tech. *Scenario 1 (SG-S1)* focuses on strengthening self-sufficiency. In this scenario, Singapore government implements new policies to boost the development of aquaculture in a drastic way, resulting in the increase of all technologies currently used as well as the introduction of the new ones mentioned above. Important annual increases for RAS, offshore and high-tech, and lower annual increase for low-tech until 2030 are assumed so that fresh fish self-sufficiency reaches 30%. This reflects important governmental help for new companies during the coming 15 years. From 2030 to 2040, moderate increases of 5% per year are assumed for high tech and SOTA, and no increase is assumed for the low tech and BAU scenarios. *Scenario 2 (SG-S2)* reflects initiatives to strengthen self-sufficiency while focusing on creating a seafood tech-hub. In this scenario, the Singapore government creates new policies to encourage the development of aquaculture production but with a strong emphasis on innovative technologies (RAS, offshore and high-tech). Compared to scenario 1, the annual increase of the production of high-tech is higher, a quicker penetration of the SOTA technologies is represented, and no increase in the production of low-tech is expected in this scenario. From 2030 to 2040, moderate increases of 5% per year are assumed for high tech, 10% for SOTA and none for low tech. The self-sufficiency goal of 30% is also reached around 2030. All the derived technological factor values (see definition in Section 3.2) used for the scenarios are documented in Supplementary Methods.

5 SIMULATION RESULTS

Figure 3 presents an overview of the Singaporean production, consumption and imports of fresh and processed fish and its evolution over the period 2017-2040 for the three simulated scenarios. The Singaporean seafood production increases significantly in the three developed scenarios. The fresh fish production increases by 10% in SG-BAU from 2017 to 2040, while it is multiplied by factors of 5.8 and

9.4 in SG-S1 and SG-S2, respectively (Figure 3). The processed fish production increases as well, albeit more moderately, by 19%, 27% and 34% in SG-BAU, SG-S1 and SG-S2 respectively. As shown in Table 3, the domestic consumption also increases in all the scenarios, for fresh and processed fish, with a final increase of 19 to 25% in 2040 compared to 2017. This trend is mainly explained by an increase of the Singaporean population, due to a modeled annual increase of 1.33% from 2017 to 2030. The consumption per capita stays relatively stable over the whole period in the three scenarios with a maximum increase of 2.9% observed in SG-S2. This difference in demand for fresh fish is covered by increasing imports in the SG-BAU scenario, while it is compensated for by the increase in production in the two explorative scenarios. Therefore, a decrease in fresh fish imports by 9% and 28% is witnessed in SG-S1 and SG-S2, respectively, between 2017 and 2040. Finally, exports, which can be seen in Figure 3 as the difference between the cumulated stacked curves and the total domestic demand, remain stable in SG-BAU, while increasing notably in SG-S1 and SG-S2 with factors of 6.5 and 12.4 for fresh fish (and factors of 1.7 and 2.3 when including processed fish) from 2017 to 2040, respectively. As a result, Singaporean SSR-SF as introduced in Section 2 increases from 10% in 2017 to 33% and 34% in 2030 and to 44% and 69% in 2040, in SG-S1 and SG-S2 respectively. Both SG-S1 and SG-S2 reach the target of 30% in 2030 exactly. The SSR-SF remains stable in SG-BAU (see Table 3).

Overall, the Singaporean aquaculture sector is subjected to an average growth of 0.4%, 8% and 11% in SG-BAU, SG-S1 and SG-S2, respectively, over the period 2017-2040. In comparison, the average annual growth of aquaculture production over the period 1990-2017 was 24% in Myanmar, 14% in Indonesia and 13% in Vietnam (FAOSTAT, 2019a). In this study, the annual aquaculture production of Singapore is found to increase from 6400 tons/yr in 2017 to 60000 tons/yr 25 years later (maximum augmentation, which corresponds to SG-S2). Comparatively, Myanmar raised its annual production from 7000 tons/yr in 1990 to more than 64000 tons/yr only 5 years later (FAOSTAT, 2019a). The simulation results are therefore validated in terms of increase potential in the light of the recent Southeast Asian aquaculture past.

Figure 3: Total domestic production, consumption and imports of fresh fish and processed fish in Singapore for the three scenarios during the period 2017-2040; the difference between the total domestic demand and the cumulated stacked curves equals the exports.

Table 3: Fresh fish self-sufficiency, total consumption and yearly averaged producer prices in Singapore in 2030 and 2040 for SG-BAU, SG-S1 and SG-S2 scenarios (BAU = business-as-usual; RAS = recirculating aquaculture systems).

	2017	2030			2040		
		BAU	Scenario 1	Scenario 2	BAU	Scenario 1	Scenario 2
Fresh seafood self-sufficiency ratio [%]	10%	8%	33%	34%	9%	44%	69%
Consumption [kg/yr/capita] (increase since 2017 [%])	29.9	29.9 (0.0%)	30.4 (1.5%)	30.2 (1.0%)	30.0 (0.2%)	30.7 (2.5%)	30.8 (2.9%)
Supply price [USD/kg] (increase since 2017 [%])							
Marine fishes	4.90	5.04 (2.9%)	3.48 (-29.1%)	3.33 (-32.0%)	5.02 (2.5%)	3.08 (-37.1%)	2.24 (-54.2%)
Freshwater fishes	10.06	10.25 (1.8%)	9.32 (-7.4%)	8.93 (-11.3%)	10.25 (1.9%)	8.91 (-11.5%)	7.82 (-22.3%)
Mollusks	0.82	1.01 (23.8%)	0.59 (-27.8%)	1.02 (25.1%)	1.02 (24.2%)	0.59 (-27.4%)	1.05 (27.8%)
Crustaceans	21.42	21.11 (-1.5%)	16.95 (-20.9%)	19.95 (-6.9%)	20.37 (-4.9%)	15.12 (-29.4%)	18.81 (-12.2%)
Processed fish	5.00	5.00 (0.0%)	4.96 (-0.7%)	4.94 (-1.1%)	5.00 (0.0%)	4.92 (-1.5%)	4.82 (-3.5%)

The supply prices of all fish types are presented in Table 3 for the years 2017, 2030 and 2040 and for the three scenarios. It represents the prices at which seafood from Singaporean fish farms are sold. The prices remain quite stable in the SG-BAU scenario, but generally decrease in the two explorative scenarios. The decrease depends on the fish type and the highest decrease is witnessed in scenario SG-S2 for marine fishes, with a price 54.2% lower in 2040 than in 2017. The notable increase of supply of that type of fish from Singapore is the main reason for this important price decrease. Other factors influence the prices of marine fishes in Singapore, such as technology improvement. Prices for other species than marine fishes do not vary more than +/-30%, which for a 25-year prospect is assumed to be reasonable. Furthermore, the prices of processed fishes remain stable along the time scope.

Figure 4a illustrates the annual production of seafood in Singapore differentiated by the different technologies in use, in 2017, 2030 and 2040 for the 3 scenarios. In 2017, as in the BAU scenarios in general, the production of marine fishes in low-tech systems dominates. In scenario S1, an increase of several technologies and species contributes to building a more proportionate aquaculture production at the country level. In scenario SG-S2, the SOTA technologies (i.e. RAS and offshore aquaculture) clearly dominate the production landscape. These observations are confirmed when looking at Figure 4b, which shows the annual distribution of the different species produced with the corresponding technologies in 2017, 2030 and 2040 for the 3 developed scenarios. In the BAU scenario, low-tech dominate the production until 2040. On the contrary, in the two explorative scenarios, it appears that the proportion of seafood produced with capture and low-tech aquaculture decreases to the advantage of production via high-tech, RAS and offshore aquaculture systems (gathered as “innovative technologies”). In 2040, the proportion of innovative technologies thus reaches 73% in SG-S1 and 90% in SG-S2, whereas it peaks only at 14% in SG-BAU (Figure 4b).

Figure 4: Domestic aquaculture production (a) and annual distribution (b) for each of the species and technologies and for the 3 scenarios, and the years 2017, 2030 and 2040.

In order to assess the actual effect of specific parameters on the results, we conducted a sensitivity analysis by varying the most uncertain inputs by $\pm 10\%$ and assessing the consequences on the production, consumption and trade quantities. The AIDS parameters, the CES/CET and the demand and expenditure elasticities were noted as the most uncertain parameters of the model. The results of the sensitivity analysis are available in Table 4, the numerical values are available in the Supplementary Results. For some sensitivity analyses, the model could not compute over the whole period, which means that the new parameters are not realistic, thus attesting to the relatively good calibration of the initial parameters. Otherwise, the model is particularly stable, with a moderate sensitivity to the choice of AIDS parameters.

The demand and expenditure elasticities only have a limited influence on the results. Therefore, for future studies on Singapore using the AsiaFish model, we recommend estimating AIDS parameters specific to the respective country in order to obtain values that are as realistic as possible.

Table 4: Results of the sensitivity analysis for Singapore for a variation of +/-10% of the tested parameters, and analysis of the output in consumption, production, imports and exports quantities.

	SG-BAU	SG-S1	SG-S2
AIDS parameters +10%	Low	N.A.	N.A.
AIDS parameters -10%	Low	Medium	Medium
Elasticities Demand +10%	Low	Low	Low
Elasticities Demand -10%	Low	Low	Low
Elasticities Expenditure +10%	Low	Low	Low
Elasticities Expenditure -10%	Low	Low	Low
CES/CET +10%	Low	Low	Low
CES/CET -10%	Low	Low	Low

“Low” means that at all 4 outputs have variation lower than 2%, “Medium” means that at all 4 outputs have variation lower than 5% and “High” means that at least one of the 4 outputs have variation higher than 5% (in absolute value) (BAU= Business-as-usual; S1= Scenario 1; S2= Scenario 2; AIDS= Almost Ideal Demand System; CES/CET are the constant elasticities of substitution of imports and constant elasticities of transformations of exports; N.A.=Not Available because the model could not compute over the whole period of time).

6 DISCUSSION ON POLICY IMPLICATIONS AND LIMITATIONS

The scenario SG-BAU, built to reflect the historic trends of Singaporean aquaculture development repeating until 2040, does not meet the Singaporean government’s objective regarding fresh seafood self-sufficiency ratio (see Section 2). This confirms that, as expected, actions need to be taken if the goal of “30 by 30” is to be reached. On the other hand, both explorative scenarios developed and tested in this paper fulfill the main objective of the Singaporean government. The target of 30% is reached in 2030 in both cases, illustrating dramatic and relatively quick increase of aquaculture production. Regarding the willingness of Singapore to become an important seafood tech hub in Asia, the proportion of innovative technologies in the aquaculture tech mix reaches 73% in SG-S1 and 90% in SG-S2 in 2040. Despite a moderate advantage for SG-S2, it is likely that Singapore would be considered as a leader in aquaculture high tech production in both cases. Therefore, at first glance, both scenarios appear like possible policy trajectories to meet the ambitions of the authorities.

However, there are substantial differences in the way the two explorative scenarios reach these targets. Singapore's new policy regarding food security explicitly aims at reducing the reliance of the country on its imports, although no quantified goal was set. Yet, despite a dramatic increase in self-sufficiency, the quantities of seafood imported over the period appear to decrease by only 9% in SG-S1 (Figure 3), due to increasing consumption on the one hand, and increasing exports on the other. Indeed, lower prices of available seafood thanks to higher domestic production enhance the consumption of seafood. At the same time, the exports prices being higher than the supply price for most species, exporting becomes more attractive to domestic producers. In SG-S2, the imports decrease by a more substantial 28%, which might be considered sufficient by the Singaporean government. Overall, the whole system dynamic evolves between 2017 and 2040 in the explorative scenarios because of the additional quantities produced and because of the price changes.

The actual benefits of increasing self-sufficiency for food security in an open global market has been largely debated by economists. Several authors and international organizations have claimed that self-sufficiency is a far from ideal solution to fight food security (Clapp, 2017). The World Bank, for example, claimed that policies that aim at improving food security through self-sufficiency by imposing import/export bans “rarely work and can exacerbate food insecurity rather than reduce it” (World Bank, 2012). These trade restrictions would create market distortion and instability that can result in lower production and higher prices (World Bank, 2012). However, these critics mainly refer to seeking theoretical “full” food self-sufficiency (i.e. SSR of 100% and no trade), which seems counterproductive from a global perspective; but it is not the goal of Singapore's new policy. The country currently has such a low fraction of domestically produced food that even after 25 years of noticeable increase, as modeled in the explorative scenarios, self-sufficiency would only reach 69% at best (SG-S2 in 2040), and only for seafood.

On top of these economic incentives, some authors have raised environmental arguments as reasons to stop seeking self-sufficiency at country level. Indeed, not all countries have the natural resources needed to be food self-sufficient, and it is more logical in a global perspective to produce certain food items where the environment is the most adequate (Fader et al., 2013). Singapore has an especially restricted availability of natural resources, and one could wonder how meaningful it is to increase its domestic production in such a context. As already stated in Section 2, the city-country has limited land availability due to its small area compared to its population. Each piece of land used for food production reduces the land available for other usages, such as housing or natural parks. Another important resource that Singapore lacks for aquaculture production is aquafeed. Because of a generally low seafood production, the domestic production of aquafeed is currently close to non-existent (FAOSTAT, 2019c). By increasing imports for this good, the

burden shifts from food imports to feed imports and inhibits potential positive effects on trade reliance vulnerability.

Nevertheless, not all technologies have the same land and resource needs. By optimizing aquaculture systems, some scarce inputs can be reduced. For example, a higher density of fishes in the grow-out phase contributes to reducing land use. Likewise, using adapted feed and optimizing the feeding schedules and associated feed amounts allows aquaculture farmers to use less feed inputs (White, 2013). Therefore, innovative and SOTA technologies are generally less reliant on land and aquafeed inputs than past and current technologies. However, electricity requirements for these high tech systems are typically higher, which is potentially a source of concern, although Singapore is currently a net exporter of electricity (EMA, 2017). Additionally, high-tech food systems require less labor, but with higher education, which is an advantage for the Singaporean socioeconomic situation. As a result, Singapore would gain by having as high as possible proportion of seafood produced via innovative technologies. This encourages a preference for SG-S2, in which low-tech aquaculture stays constant until 2040 and the proportion of high-tech and SOTA production reaches 90%.

Overall, compared to SG-S1, scenario SG-S2 appears to have a higher decrease of imports (-28%), a higher final self-sufficiency ratio (69%) and a bigger proportion of innovative/future technologies (90%). Therefore, this scenario is the best option for the Singaporean government to reach its policy goals, given the current socioeconomic and environmental constraints of the country.

Thus, the findings in this paper support the idea that there is potential for the new aquaculture policy to achieve its objectives in Singapore, provided that the right actions are undertaken. Subsequently, using the trends of scenario SG-S2 to build concrete decisions will likely increase the odds of fulfilling that new policy within the timeframe set by the government, and help to avoid the past failures witnessed in high-income countries. As such, these findings illustrate the use of forecasting socioeconomic models to support detailed decision-making to potentially benefit new aquaculture growth policies and increase their chance to evolve from illusionary dreams to successful local “blue revolutions”. Furthermore, the methodological framework we developed in this paper can be used to assess other countries’ aquaculture policies. The structure can be re-used with few adjustments and the input data adapted to another case. That way, new aquaculture growth policies can be assessed and scientific-based advice can be provided to decision-makers on which technologies or species to prioritize to increase chances to reach the targeted overall growth. Constraints on social and environmental problematics can be included in the study by enforcing new parameters or additional thresholds on existing ones. This flexibility is a strength when it comes to adaptation to other case studies.

These findings should however be cautioned with a number of uncertainties and limitations. First, data availability is problematic for Singapore. The model inputs regarding production, consumption and trade for the current situation were retrieved from the FAO databases, which might induce errors compared to data obtained directly from the local government. Ideally, each product sold as seafood should constitute one separate category, differentiated by species and product type (e.g. entire fish, fillet or frozen fillet), as consumers might have different behaviors regarding each of them. However, this is near impossible when it comes to seafood because of the sheer number of products. According to the FAO, 347 different seafood products were produced, imported or exported in Singapore in 2011 (FAOSTAT, 2019c). In the current study, finding adequate and representative data to populate the model was already challenging for Singapore, which only accounts for 10 categories. Demand and expenditure elasticities were not differentiated by species and generic seafood elasticities were used, leading to a debatable representativeness of these data. The AIDS parameters in the consumer core were not available for Singapore, and were therefore extracted from those of other countries. Finally, the constant elasticities of substitution for imports and constant elasticities of transformation for exports were based on expert opinion with no empirical study to support them. Similarly, little data can be expected in countries that are not in Europe (Thong, 2012; Tiffin et al., 2011; Xie and Myrland, 2012) or North-America (Pomboza and Mbaga, 2007; Zhou, 2015). Using data with minimal geographical representativeness might result in large uncertainties in the model. This data paucity therefore calls for more elasticities and demand studies regarding seafood in order to expand the pool of data usable in analysis studies like ours.

Another limitation of the study lies in the structure of the AsiaFish model and its ability to capture the market mechanisms. The equations in the model are defined based on economic theories and were selected by the developers of the first version of the model as being the most realistic while remaining simple to implement (to preserve the model operability - Dey et al., 2005a). Consequently, it means that not all the complex mechanisms that take place in reality could be integrated. For example, the AsiaFish model was not built to handle important market changes; as a result dramatic and abrupt changes, e.g. from disruptive technology implementation or from sudden policy bans, could lead to unfeasible optimizations (i.e. collapse of the model). Another shortcoming in the current model structure is that all technologies are modeled in the same way, and react similarly to market changes. Thus, no difference is made between mature technologies and emerging ones. Therefore, in future developments of the AsiaFish model, we recommend addressing these limitations and re-parameterizing the equations to better capture market mechanisms.

Additionally, our model is built based on the “*ceteris paribus*” principle, and therefore some economic parameters that are likely to change in the future are kept constant, such as exchange rates, inflation rates or growth of income per capita. Accounting for these changes might change the results of the simulations

and therefore the results of the study. For instance, an increasing income per capita would contribute to higher consumption of seafood, as the implemented expenditure elasticity of seafood is positive, and thereby have an effect on trades. Similarly, variations of the exchange rates would influence of imports and exports quantities. These changes would influence the SSR and therefore the benefits of each scenario. Keeping these parameters constant induces uncertainties in the model. However, forecasting these economic parameters is by definition impossible and any attempt would be accompanied by great uncertainties as well. Thus, future practitioners of the model should consider their implementation with care.

Furthermore, in our study, we decided to focus on changing technological growth factors to express a policy implementation. However, the government incentives under study may lead to repercussions on other parameters of the model over time, for example the elasticities or the applicability of the considered theories and associated equations. A market study could help define these changes and help a practitioner implement them in a revised version of the model, eventually improving the policy support, this improvement would in turn increase the likelihood of obtaining the desired consequences.

Finally, the current analysis only considers the seafood sector, ignoring the other sectors of the Singaporean economy. Promoting seafood production might translate to drawing resources from other industries. This can result in potential losses in other sectors of the country's economy, which could be economic, labor-related, resource-related or land-related. As such, the current analysis ignores the net impacts on the economy as a whole, and an analysis of Singaporean industries' interconnection would make the results more comprehensive. General-equilibrium models with fish products produced in separate sectors are capable of analyzing the interconnectedness of different industries in the economy and therefore take possible losses in other sectors due to the increase in seafood production into account. Such modeling, however, remains an issue for future research.

7 CONCLUSIONS

We developed an adapted version of the Asiafish model to allow foresight into the implications of novel aquaculture policies with a high level of technological disaggregation of supply. The methodology proposed was applied on Singapore and its ambitious new aquaculture policies. Both scenarios developed fulfil the government goals in terms of seafood self-sufficiency, but scenario SG-S2 presents additional advantages that make it the best option defined in the study. Information, such as that gained through the application of the Asiafish model, on potential consequences of the policy can prove useful for policy-makers and could help them anticipate and better define and/or refine their long-term strategies and goals.

However, the AsiaFish model only gives a predisposition for the future and is based on a *ceteris paribus* assumption. Therefore, this study should be used as a preliminary step to assess a new policy in broad terms, allowing for highlighting potential issues, inconsistencies or unwanted consequences. A more thorough economic, social or environmental study can be subsequently conducted to help determine if the spotted problems are realistic and what their extent could be. Indeed, authorities may rely on other criteria than pure economically-driven ones, and policy evaluation should thus cover a broad perspective to address all aspects of food sustainability, security and safety. As part of the sustainability dimension, an important driver of policy changes, in particular in developed countries, is environmental protection. Different aquaculture production systems embed a variety of damages to ecosystems, human health and natural resources (Bohnes et al., 2019). These should be assessed quantitatively using comprehensive tools such as the ISO-standardized life cycle assessment methodology, which enables quantification of environmental impacts of aquaculture systems in a life cycle perspective, i.e. from extraction of raw materials through production and use up through the end-of-life of the system (Bohnes and Laurent, 2018; ISO, 2006a,b). The integration of such an assessment tool within the evaluation framework, as developed in this study, could allow performing combined assessments of economic and environmental consequences associated with seafood policies at national scale, identifying potential trade-offs that may result between the two dimensions, and eventually enable provision of more holistic and informed decision support for policy-makers.

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SUPPLEMENTARY INFORMATION

Are aquaculture growth policies in high-income countries due diligence or illusionary dreams? Foreseeing policy implications on seafood production in Singapore

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Table of Contents

1	Supplementary methods.....	2
1.1	Data sources and main assumptions.....	2
1.2	Change in technological growth factors for the 3 scenarios (%)	4
2	Supplementary results	5
2.1	Scenarios	5
2.2	Sensitivity analysis.....	9

1 SUPPLEMENTARY METHODS

1.1 DATA SOURCES AND MAIN ASSUMPTIONS

Table S1: List of the sources

Data	Source
Proportion of re-exports	Domestic Exports and Re-exports By Commodity Division, Monthly (SINGSTAT)
Aquaculture production (quantity and value)	FISHSTAT FAO - Global aquaculture production 1950-2016
Capture production (quantity)	FISHSTAT FAO - Global capture production 1950-2016
Processed fish production (quantity)	FISHSTAT FAO - Fisheries commodities production and trade 1976-2016
Imports and exports of fresh and processed products (quantity and value)	FISHSTAT FAO - Fisheries commodities production and trade 1976-2016
Exchange rate USD/SGD	SINGSTAT
Seafood consumption in Singapore	AVA - https://www.ava.gov.sg/docs/default-source/default-document-library/per-capita-consumption-(2015) [Accessed on 17-12-2018]
Singapore population	SINGSTAT
Average members of a household in SG	SINGSTAT (M810371)
Average Monthly Household Expenditure for Food, Non-food, and all the categories chosen for the stage 2 AIDS function	SINGSTAT
Average Monthly Household Income from Work Per Household Member	SINGSTAT

List of main assumptions of the Singapore model:

- Algae, sharks, aquatic mammals, corals, cephalopods, ornamental fishes, frogs are excluded.
- Re-exports are removed. Proportion of re-export are chosen to add up at 61% (in value) (source: SINGSTAT) and that production is higher than exports in quantity for each species.
 - o Proportion of re-export by species in 2011:
 - Marine fishes: 45%
 - Freshwater fishes: 40%
 - Mollusks: 60%
 - Crustaceans: 80%
 - Processed: 60,17%
- Production of feed is considered negligible in Singapore and is therefore not removed.
- Food from outside home represents 64% of the total food expenditure in Singapore (FISHSTAT), it is therefore considered that it cannot be part of the "Other food" category. It is considered that the repartition between different food categories is the same for food from home and food from the outside, and the expenditure is split as:

- $\text{Expe_food } i = (\text{Expe_all food}) / ((\text{Expe_all food} - \text{Expe_food away from home}))$
*Expe_food i at home
- No home production in Singapore (only companies).
- Proportion of seafood produced with different technologies in 2011 (*Source: FAO FISHSTAT):
 - Marine fishes
 - Capture: 29,65%*
 - Low-Tech: 68,33%
 - High-Tech: 2,00%
 - RAS: 0,01%
 - Offshore : 0,01%
 - Freshwater fishes
 - Low-Tech: 99,99%
 - RAS: 0,01%
 - Crustaceans
 - Capture 83,82%*
 - High-tech aquaculture 16,18%*
- Producer price of processed fish is the same than the producer price of fresh fish from the same species.
- Price of intermediate demand in fresh fish is equal to the price of the same species for fresh sells, because the production is so low that there is no difference in quality between the fish sold fresh and the one that will be used for the production of processed fish.
- When the supply prices for capture is unknown, it is set equal to producer price from aquaculture.
- Proportion of the seafood supply going to processed fish production (intermediate demand):
 - Marine fishes: 80%
 - Freshwater fishes: 0%
 - Mollusks: 30%
 - Crustaceans: 5%

Table S2: Choice of the elasticities

	Species	Value	Geographical zone	Year	Source
Demand elasticities (own-price)	All species	-0,325	Singapore	2005	Muhammad <i>et al.</i> (2012)*
Demand elasticities (own-price)	All species	0	All the products are considered non-substitutable, nor complementary		
Supply elasticities	All species	0	The quantity produced is, in the case of capture, independent from the price because of the intrinsic nature of the supply, for the case of aquaculture, highly more dependent on other factors than the price.		
Expenditure elasticities	All species	0,443	Singapore	2005	Muhammad <i>et al.</i> (2012)*
Constant elasticity of substitution (CES)	All species	4.0	High willingness of the government to reduce imports.		
Constant elasticity of transformation (CET)	All species	0.5	Singapore being a big importer, the quantities exported are quite independent from the prices of exports. Therefore, CET is chosen relatively small.		

*Muhammad, A., Seale, J.L., Meade, B. and Regmi, A. (2012) *International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data*. Ssrn.

1.2 CHANGE IN TECHNOLOGICAL GROWTH FACTORS FOR THE 3 SCENARIOS (%)

Table S3: Change in technological factor growth for the Business-As-Usual scenario:

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
MFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MFLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MFHT	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
MFRAS	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
MFOF	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
FFLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FFRAS	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
MOLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRHT	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Table S4: Change in technological factor growth for the scenario 1:

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
MFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MFLT	0	5	5	5	5	5	5	5	5	5	5	5	5	2	0	0	0	0	0	0	0	0	0	0
MFHT	0	50	40	30	30	30	30	30	30	30	30	30	30	15	5	5	5	5	5	5	5	5	5	5
MFRAS	0	200	150	100	100	100	100	100	100	100	100	100	100	50	5	5	5	5	5	5	5	5	5	5
MFOF	0	200	150	100	100	100	100	100	100	100	100	100	100	5	5	5	5	5	5	5	5	5	5	5
FFLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FFRAS	0	200	150	100	100	100	100	100	100	100	100	100	100	50	5	5	5	5	5	5	5	5	5	5
MOLT	0	5	5	5	5	5	5	5	5	5	5	5	5	2	0	0	0	0	0	0	0	0	0	0
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRHT	0	30	25	20	20	20	20	20	20	20	20	20	20	10	5	5	5	5	5	5	5	5	5	5

Table S5: Change in technological factor growth for the scenario 2:

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
MFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MFLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MFHT	0	40	30	20	20	20	20	20	20	20	20	20	20	10	5	5	5	5	5	5	5	5	5	5
MFRAS	0	200	150	150	150	100	100	100	100	100	100	100	100	50	10	10	10	10	10	10	10	10	10	10
MFOF	0	200	150	150	150	100	100	100	100	100	100	100	100	50	10	10	10	10	10	10	10	10	10	10
FFLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FFRAS	0	200	150	150	150	100	100	100	100	100	100	100	100	50	10	10	10	10	10	10	10	10	10	10
MOLT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRHT	0	20	15	10	10	10	10	10	10	10	10	10	10	7	5	5	5	5	5	5	5	5	5	5

2 SUPPLEMENTARY RESULTS

2.1 SCENARIOS

Table S6: Aggregate quantities excluding processed fish [000 tons] for the Business-as-usual scenario

Period	Domestic output	Imports	Exports	Consumption	Processing
2017	6.39	61.32	1.45	30.10	36.16
2018	6.40	62.18	1.45	30.50	36.64
2019	6.42	63.05	1.45	30.90	37.12
2020	6.44	63.93	1.45	31.31	37.61
2021	6.46	64.83	1.45	31.73	38.10
2022	6.48	65.73	1.45	32.15	38.61
2023	6.50	66.65	1.45	32.57	39.12
2024	6.52	67.58	1.45	33.01	39.63
2025	6.54	68.52	1.46	33.45	40.16
2026	6.56	69.47	1.46	33.89	40.69
2027	6.59	70.44	1.46	34.34	41.22
2028	6.61	71.42	1.46	34.80	41.77
2029	6.64	72.41	1.47	35.26	42.33
2030	6.67	73.41	1.47	35.73	42.89
2031	6.70	73.40	1.47	35.74	42.89
2032	6.73	73.39	1.48	35.74	42.90
2033	6.76	73.37	1.48	35.75	42.90
2034	6.80	73.36	1.49	35.76	42.91
2035	6.84	73.34	1.49	35.76	42.92
2036	6.87	73.32	1.50	35.77	42.93
2037	6.91	73.30	1.50	35.78	42.94
2038	6.96	73.29	1.51	35.79	42.95
2039	7.00	73.27	1.52	35.80	42.95
2040	7.05	73.24	1.52	35.80	42.96

Table S7: Aggregate quantities excluding processed fish [000 tons] for the scenario 1

Period	Domestic output	Imports	Exports	Consumption	Processing
2017	6.39	61.32	1.45	30.10	36.16
2018	6.74	61.97	1.52	30.52	36.67
2019	7.13	62.60	1.60	30.95	37.18
2020	7.54	63.23	1.68	31.38	37.70
2021	8.00	63.84	1.78	31.82	38.24
2022	8.53	64.41	1.89	32.27	38.78

2023	9.16	64.93	2.02	32.73	39.34
2024	9.95	65.37	2.19	33.20	39.92
2025	10.96	65.68	2.42	33.69	40.52
2026	12.35	65.75	2.74	34.20	41.15
2027	14.42	65.43	3.25	34.75	41.86
2028	17.73	64.51	4.10	35.38	42.76
2029	23.34	62.23	5.62	36.09	43.86
2030	26.52	61.00	6.53	36.58	44.41
2031	27.34	60.59	6.75	36.64	44.53
2032	28.21	60.21	6.99	36.72	44.70
2033	29.12	59.83	7.23	36.82	44.90
2034	30.07	59.44	7.49	36.91	45.10
2035	31.07	58.88	7.77	36.98	45.21
2036	32.13	58.30	8.06	37.04	45.33
2037	33.23	57.69	8.37	37.11	45.45
2038	34.39	57.06	8.69	37.18	45.57
2039	35.61	56.40	9.04	37.26	45.71
2040	36.89	55.71	9.40	37.34	45.85

Table S8: Aggregate quantities excluding processed fish [000 tons] for the scenario 2

Period	Domestic output	Imports	Exports	Consumption	Processing
2017	6.39	61.32	1.45	30.10	36.16
2018	6.47	62.14	1.46	30.51	36.65
2019	6.56	62.97	1.47	30.92	37.14
2020	6.64	63.82	1.49	31.34	37.64
2021	6.75	64.65	1.51	31.76	38.14
2022	6.89	65.48	1.54	32.18	38.65
2023	7.10	66.28	1.58	32.62	39.18
2024	7.42	67.01	1.65	33.07	39.72
2025	7.97	67.61	1.78	33.52	40.28
2026	8.95	67.95	2.03	34.00	40.87
2027	10.76	67.75	2.49	34.50	41.53
2028	14.24	66.54	3.42	35.04	42.31
2029	20.99	62.94	5.34	35.64	42.96
2030	27.65	60.78	7.30	36.41	44.73
2031	29.70	59.67	7.91	36.50	44.97
2032	31.96	58.43	8.60	36.58	45.20
2033	34.43	57.07	9.37	36.68	45.46
2034	37.14	55.61	10.22	36.78	45.75
2035	40.12	54.03	11.16	36.90	46.09
2036	43.39	52.33	12.22	37.03	46.46

2037	46.98	50.49	13.40	37.18	46.89
2038	50.92	48.53	14.72	37.36	47.38
2039	55.25	46.44	16.19	37.55	47.95
2040	60.01	44.21	17.85	37.77	48.60

Table S9: Production of each category and each year [000 tons] for Business-as-usual scenario

period	MFCAP	MFLT	MFHT	MFRAS	MFOF	FFLT	FFRAS	MO	CRCAP	CRAQ	Proc
2017	0.75	4.41	0.11	0.00	0.00	0.29	0.00	0.35	0.27	0.21	44.35
2018	0.75	4.41	0.11	0.00	0.00	0.29	0.00	0.35	0.27	0.22	44.94
2019	0.75	4.41	0.12	0.00	0.00	0.29	0.00	0.35	0.27	0.23	45.53
2020	0.75	4.41	0.12	0.00	0.00	0.29	0.00	0.35	0.27	0.25	46.13
2021	0.75	4.41	0.13	0.00	0.00	0.29	0.00	0.35	0.27	0.26	46.73
2022	0.75	4.41	0.13	0.00	0.00	0.29	0.00	0.35	0.27	0.27	47.35
2023	0.75	4.41	0.14	0.00	0.00	0.29	0.00	0.35	0.27	0.28	47.97
2024	0.75	4.41	0.15	0.00	0.00	0.29	0.00	0.35	0.27	0.30	48.61
2025	0.75	4.41	0.16	0.00	0.00	0.29	0.00	0.35	0.27	0.31	49.25
2026	0.75	4.41	0.16	0.00	0.00	0.29	0.00	0.35	0.27	0.33	49.90
2027	0.75	4.41	0.17	0.00	0.00	0.29	0.00	0.35	0.27	0.35	50.56
2028	0.75	4.41	0.18	0.00	0.00	0.29	0.00	0.35	0.27	0.36	51.23
2029	0.75	4.41	0.19	0.00	0.00	0.29	0.00	0.35	0.27	0.38	51.91
2030	0.75	4.41	0.20	0.00	0.00	0.29	0.00	0.35	0.27	0.40	52.60
2031	0.75	4.41	0.21	0.00	0.00	0.29	0.00	0.35	0.27	0.42	52.60
2032	0.75	4.41	0.22	0.00	0.00	0.29	0.00	0.35	0.27	0.44	52.61
2033	0.75	4.41	0.23	0.00	0.00	0.29	0.00	0.35	0.27	0.46	52.62
2034	0.75	4.41	0.24	0.00	0.00	0.29	0.00	0.35	0.27	0.49	52.63
2035	0.75	4.41	0.25	0.00	0.00	0.29	0.00	0.35	0.27	0.51	52.64
2036	0.75	4.41	0.27	0.00	0.00	0.29	0.00	0.35	0.27	0.54	52.65
2037	0.75	4.41	0.28	0.00	0.00	0.29	0.00	0.35	0.27	0.56	52.66
2038	0.75	4.41	0.29	0.00	0.00	0.29	0.00	0.35	0.27	0.59	52.67
2039	0.75	4.41	0.31	0.00	0.00	0.29	0.00	0.35	0.27	0.62	52.68
2040	0.75	4.41	0.32	0.00	0.00	0.29	0.00	0.35	0.27	0.65	52.69

Table S10: Production of each category and each year [000 tons] for scenario 1

period	MFCAP	MFLT	MFHT	MFRAS	MFOF	FFLT	FFRAS	MO	CRCAP	CRAQ	Proc
2017	0.75	4.41	0.11	0.00	0.00	0.29	0.00	0.35	0.27	0.21	44.35
2018	0.75	4.63	0.16	0.00	0.00	0.29	0.00	0.37	0.27	0.28	44.97
2019	0.75	4.86	0.22	0.00	0.00	0.29	0.00	0.39	0.27	0.34	45.60
2020	0.75	5.10	0.29	0.01	0.01	0.29	0.00	0.41	0.27	0.41	46.24
2021	0.75	5.36	0.37	0.02	0.02	0.29	0.00	0.43	0.27	0.50	46.89
2022	0.75	5.63	0.49	0.03	0.03	0.29	0.00	0.45	0.27	0.60	47.56

2023	0.75	5.91	0.63	0.06	0.06	0.29	0.00	0.47	0.27	0.71	48.25
2024	0.75	6.20	0.82	0.13	0.13	0.29	0.01	0.50	0.27	0.86	48.96
2025	0.75	6.52	1.07	0.25	0.25	0.29	0.01	0.52	0.27	1.03	49.69
2026	0.75	6.84	1.39	0.51	0.51	0.29	0.03	0.55	0.27	1.23	50.47
2027	0.75	7.18	1.80	1.01	1.01	0.29	0.06	0.58	0.27	1.48	51.34
2028	0.75	7.54	2.34	2.02	2.02	0.29	0.11	0.61	0.27	1.78	52.45
2029	0.75	7.92	3.05	4.04	4.04	0.29	0.22	0.64	0.27	2.13	53.80
2030	0.75	8.08	3.50	6.06	4.24	0.29	0.34	0.65	0.27	2.34	54.46
2031	0.75	8.08	3.68	6.37	4.46	0.29	0.35	0.65	0.27	2.46	54.62
2032	0.75	8.08	3.86	6.68	4.68	0.29	0.37	0.65	0.27	2.59	54.83
2033	0.75	8.08	4.06	7.02	4.91	0.29	0.39	0.65	0.27	2.71	55.06
2034	0.75	8.08	4.26	7.37	5.16	0.29	0.41	0.65	0.27	2.85	55.32
2035	0.75	8.08	4.47	7.74	5.42	0.29	0.43	0.65	0.27	2.99	55.45
2036	0.75	8.08	4.70	8.12	5.69	0.29	0.45	0.65	0.27	3.14	55.59
2037	0.75	8.08	4.93	8.53	5.97	0.29	0.47	0.65	0.27	3.30	55.74
2038	0.75	8.08	5.18	8.96	6.27	0.29	0.50	0.65	0.27	3.46	55.89
2039	0.75	8.08	5.44	9.40	6.58	0.29	0.52	0.65	0.27	3.64	56.06
2040	0.75	8.08	5.71	9.87	6.91	0.29	0.55	0.65	0.27	3.82	56.23

Table S11: Production of each category and each year [000 tons] for scenario 2

period	MFCAP	MFLT	MFHT	MFRAS	MFOF	FFLT	FFRAS	MO	CRCAP	CRAQ	Proc
2017	0.75	4.41	0.11	0.00	0.00	0.29	0.00	0.35	0.27	0.21	44.35
2018	0.75	4.41	0.15	0.00	0.00	0.29	0.00	0.35	0.27	0.25	44.95
2019	0.75	4.41	0.19	0.00	0.00	0.29	0.00	0.35	0.27	0.29	45.55
2020	0.75	4.41	0.23	0.01	0.01	0.29	0.00	0.35	0.27	0.32	46.16
2021	0.75	4.41	0.28	0.03	0.03	0.29	0.00	0.35	0.27	0.35	46.78
2022	0.75	4.41	0.33	0.05	0.05	0.29	0.00	0.35	0.27	0.39	47.40
2023	0.75	4.41	0.40	0.10	0.10	0.29	0.01	0.35	0.27	0.43	48.05
2024	0.75	4.41	0.48	0.20	0.20	0.29	0.01	0.35	0.27	0.47	48.71
2025	0.75	4.41	0.57	0.40	0.40	0.29	0.02	0.35	0.27	0.52	49.40
2026	0.75	4.41	0.69	0.79	0.79	0.29	0.04	0.35	0.27	0.57	50.13
2027	0.75	4.41	0.82	1.58	1.58	0.29	0.09	0.35	0.27	0.63	50.93
2028	0.75	4.41	0.99	3.16	3.16	0.29	0.18	0.35	0.27	0.69	51.89
2029	0.75	4.41	1.19	6.31	6.31	0.29	0.35	0.35	0.27	0.76	52.69
2030	0.75	4.41	1.30	9.47	9.47	0.29	0.52	0.35	0.27	0.81	54.85
2031	0.75	4.41	1.37	10.42	10.42	0.29	0.58	0.35	0.27	0.85	55.15
2032	0.75	4.41	1.44	11.46	11.46	0.29	0.64	0.35	0.27	0.89	55.44
2033	0.75	4.41	1.51	12.61	12.61	0.29	0.70	0.35	0.27	0.94	55.76
2034	0.75	4.41	1.59	13.87	13.87	0.29	0.77	0.35	0.27	0.99	56.12
2035	0.75	4.41	1.67	15.25	15.25	0.29	0.85	0.35	0.27	1.04	56.52
2036	0.75	4.41	1.75	16.78	16.78	0.29	0.93	0.35	0.27	1.09	56.98

2037	0.75	4.41	1.84	18.46	18.46	0.29	1.02	0.35	0.27	1.14	57.51
2038	0.75	4.41	1.93	20.30	20.30	0.29	1.12	0.35	0.27	1.20	58.11
2039	0.75	4.41	2.02	22.33	22.33	0.29	1.24	0.35	0.27	1.26	58.80
2040	0.75	4.41	2.13	24.57	24.57	0.29	1.36	0.35	0.27	1.32	59.60

2.2 SENSITIVITY ANALYSIS

Table S12: Results of the sensitivity analysis in the form of normalized sensitivity coefficients, or $(\Delta \text{output/output}) / (\Delta \text{input/input})$ (AIDS=Almost Ideal Demand Function parameters varying by +/-10%; Elas Dem=Elasticity of demand varying by +/-10%; Elas Exp= Expenditure elasticity varying by +/-10%; CES/CET= CES and CET varying by +/-10%; N.A.=Not Available because the model could not compute over the whole period of time)

		Domestic output	Imports	Exports	Consumption	Processing
BAU	AIDS +10%	-	- 0.03	-	- 0.02	- 0.03
	AIDS -10%	-	- 0.04	-	- 0.03	- 0.03
	Elas Dem +10%	-	- 0.00	-	-	- 0.00
	Elas Dem -10%	-	0.00	-	- 0.00	0.00
	Elas Exp +10%	-	- 0.00	-	- 0.00	- 0.00
	Elas Exp -10%	-	0.00	-	0.00	0.00
	CES/CET +10%	-	- 0.01	-	- 0.01	- 0.01
	CES/CET -10%	-	- 0.00	-	- 0.00	- 0.00
S1	AIDS +10%	n.a.	n.a.	n.a.	n.a.	n.a.
	AIDS -10%	-	0.27	- 0.03	0.19	0.18
	Elas Dem +10%	-	0.03	- 0.00	0.02	0.03
	Elas Dem -10%	-	- 0.03	0.00	- 0.02	- 0.03
	Elas Exp +10%	-	- 0.01	-	- 0.00	- 0.00
	Elas Exp -10%	-	0.01	- 0.00	0.00	0.00
	CES/CET +10%	-	- 0.07	0.00	- 0.04	- 0.06
	CES/CET -10%	-	0.09	- 0.00	0.05	0.07
S2	AIDS +10%	n.a.	n.a.	n.a.	n.a.	n.a.
	AIDS -10%	-	0.33	- 0.03	0.19	0.17
	Elas Dem +10%	-	0.09	- 0.01	0.03	0.07
	Elas Dem -10%	-	- 0.10	0.02	- 0.03	- 0.07
	Elas Exp +10%	-	- 0.01	0.00	- 0.00	- 0.00
	Elas Exp -10%	-	0.01	- 0.00	0.00	0.00
	CES/CET +10%	-	- 0.13	0.02	- 0.05	- 0.09
	CES/CET -10%	-	0.16	- 0.03	0.06	0.11

PAPER IV

Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore

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Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore

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ABSTRACT

In a context of global population growth and increased food demand, the development of the aquaculture industry has become essential, and aquaculture development policies have flourished. However, aquaculture is associated with various environmental impacts, such as eutrophication or climate change. It is therefore important to assess the environmental sustainability of aquaculture development, for example through the use of life cycle assessment (LCA). Yet, there is limited application of LCA to aquaculture technologies in Asian countries, where most aquaculture growth is taking place, and none of them has assessed environmental impacts of both current and future aquaculture systems. Here, we took Singapore as an example of country, which has recently developed aquaculture development strategies, and we performed a comparative LCA of eight Singaporean aquaculture production systems, thus covering all relevant existing and potential future production technologies. To do so, we built comprehensive life cycle inventories (LCI) of 8 categories of aquaculture production for four species groups in Singapore, for both 2017 and 2040. Two options of feed evolution were assessed in 2040: increasing the part of fishmeal and fish oil (FMFO) produced from trimmings and replacing FMFO by insect-based meal and algal oil. We assessed 11 environmental impact categories, including net primary production use. Overall, per unit of edible seafood produced, the production of marine fishes in sea cages near the shore and in recirculating aquaculture systems were found to be the most attractive options to limit the environmental impacts while increasing seafood production in Singapore. Freshwater fishes produced in concrete ponds were found to have the lowest impact indicator scores per ton of edible seafood produced, but these results were highly sensitive to methodological choices and it was deemed constrained by limited potential to increase its production capacity in the future. Increasing the part of FMFO produced from trimmings is found to have more environmental benefits than insect-based meal. However, the uncertainty concerning the future

technologies is high, particularly for anticipating future technologies. Further research is therefore needed to refine the assessment of the potential environmental impacts of future aquaculture production systems, including focusing on novel technologies and new feed options specifically adapted to each country. Meanwhile, we recommend analysts to take inspiration from and build on the detailed LCIs developed in the current study to support assessments of aquaculture systems in other underresearched Asian countries.

KEYWORDS

Life cycle assessment; LCA; LCI; life cycle inventory; seafood; prospective assessment; future food production.

1 INTRODUCTION

Growing world population and higher average incomes globally are drivers of the current increase in food demand (FAO, 2018). To meet that demand, aquaculture has been the fastest growing food industry globally for several decades now, and is expected to continue in the coming years despite a slight decrease in annual growth rates (FAO, 2016). Furthermore, together with wild capture, aquaculture participates to the availability of healthier diets associated with seafood (HLPE, 2014). In that context, aquaculture industry development is important for many countries, explaining why dedicated policies have emerged over the years in both high- and low-income countries. With an ambition to trigger their own “blue growth”, both historical aquaculture producers, like Norway, and new comers, like Nigeria, have shown a willingness to develop their seafood farming industry (Eikeset et al., 2018; FAO, 2018). Among the new comers, a prominent example is the city-state of Singapore, whose government has elaborated an audacious aquaculture development plan that aims at increasing its seafood production manifold by 2030 (Zulkifli, 2019). Aquaculture appears as a key to strengthen Singapore’s food security by decreasing its reliance on imports, which currently represent more than 90% of their food consumption (SFA, 2019a).

Despite these socioeconomic benefits, aquaculture production remains associated with a number of environmental impacts, due to e.g. its emissions of nutrients and chemicals to water, its interactions with local biodiversity, its energy use and its reliance on capture for feed production (Diana, 2009; Naylor et al., 2000). These participate to environmental problems such as eutrophication, climate change, degradation of local biodiversity and resource depletion (Bohnes et al., 2019; Ottinger et al., 2016). Various aquaculture technologies exist, e.g. depending on the seafood group, the levels of intensity, or whether it is in closed or open systems. Each technology typically has its own specificities with regard to types of environmental impacts. New technologies are often developed to reduce specific impacts of existing aquaculture systems,

but at the same time they might shift the environmental burden by increasing other relevant types of impacts. For example, developing closed systems primarily aims at reducing nutrient emissions in open waters causing eutrophication, but to recreate an environment favorable to fish growth, energy requirements are usually high hence increasing contribution to climate change impacts when that energy stems from fossil-based sources. It is therefore important to ensure that aquaculture development occurs with as few environmental impacts as possible by choosing the technologies with the lower environmental burdens.

Life cycle assessment (LCA) is an ISO-standardized methodology that allows to quantify a large variety of environmental impacts from aquaculture systems and has been widely used (e.g. Abdou et al., 2017; Biermann and Geist, 2019; Le Féon et al., 2019; Vogel et al., 2019; see review in Bohnes et al. 2019). LCA can be used to compare the environmental impacts of several systems through their whole life cycle, i.e. from raw materials extraction, through production and use/operation of the system, up to its final recycling and disposal, thus preventing environmental burden-shifting from one life cycle stage to another or from one environmental problem to another (ISO, 2006a, 2006b). It can also be used to assess and identify which life cycle stages, processes or substances carry the highest environmental impacts.

LCA have been used to assess various aquaculture technologies, among which longstanding ones such as ponds (e.g. Astudillo et al., 2015; Pelletier and Tyedmers, 2010) or extensive polyculture (e.g. Aubin et al., 2015; Medeiros et al., 2017), as well as more recent technologies like recirculating aquaculture systems (RAS, e.g. Dekamin et al., 2015; Sun, 2009) or aquaponics (e.g. Cohen et al., 2018; Forchino et al., 2017). Several studies compared different technologies for the same species production, as in Liu et al. (2016), where the production of salmon in sea cages is compared with its production in RAS. The growth of aquaculture production can originate from the development of existing technologies, the implementation of new technologies or a combination of both scenarios. Therefore, only by simultaneously assessing existing technologies for possibility of improvements as well as potential future technologies can the most environmentally friendly options be identified. However, to the authors' knowledge, none of the existing LCA studies compared current and potential future technologies.

The lack of available life cycle inventories (LCI), which compile energy and materials requirements, waste generation, pollutant emissions and resource use of specific aquaculture activities, was identified as a major gap in LCA literature applied to aquaculture systems and may explain this trend (Bohnes and Laurent, 2019; Henriksson et al., 2012). Many published LCA studies indeed do not report transparently the LCI data used, preventing their further utilization. Moreover, available LCI databases, such as Ecoinvent (Wernet et al., 2016) or Agri-footprint (Durlinger et al., 2017), contain very little information on aquaculture. In addition, there is a mismatch in the literature between the type of aquaculture systems studied in LCA and their relative importance in the global aquaculture technology landscape. There is thus a particularly low

proportion of LCA studies focusing on Asian countries, while around 90% of the world aquaculture seafood production originates from this continent (Bohnes et al., 2019). In light of the above limitations, there is therefore a strong need for more transparent and comprehensive LCI data on Asian technologies.

The objective of our study is to address this need by assessing environmental impacts of a large variety of different technologies and species used in the Singaporean aquaculture industry today and that can potentially be used in the future. To do so, we aim to (i) create and transparently document life cycle inventories for all identified aquaculture systems, existing and future, in Singapore; (ii) perform a comparative LCA study between current technologies and novel technologies assuming their implementation (taking 2017 as reference year); and (iii) conduct a prospective comparative LCA study and associated contribution analyses of all technologies for the reference year 2040, including two different feed options. This latter objective accounts for evolutions of the electricity mix, as well as a potential optimization of the technologies reflected by a reduction of energy, water and feed requirements. In a majority of the LCA studies conducted so far, feed has been highlighted as the main contributor to most environmental impacts (Bohnes et al., 2019), hence the comparison of two feed options in year 2040. The case of Singapore was selected because it contributes to filling the lack of LCIs and LCAs on Asian aquaculture and because of its recently raised relevance due to the new policy of the Singaporean government, which aimed at increasing its aquaculture production in the coming years.

2 MATERIAL AND METHODS

LCA is an iterative process that is structured into four phases according to the ISO standards: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation of the results (ISO, 2006a, 2006b). We first describe Singapore's aquaculture industry in term of current as well as potential future species and technologies (Section 2.1), before detailing the main phases of our LCA study (Sections 2.2-2.4).

2.1 DESCRIPTION OF SINGAPOREAN AQUACULTURE INDUSTRY

2.1.1 Aquaculture landscape in Singapore

Currently, aquaculture is a small industry in Singapore, and only 10% of the seafood consumed is produced locally (SFA, 2019a). Among the estimated 130 farms existing in 2017, about 115 produced marine fishes for a total of 4514 tons that year, mostly of high value such as barramundi, pompano or milkfish (FAOSTAT, 2019; SFA, 2019b). The remaining farms offered a small production of freshwater fishes (e.g. catfish and Tilapia), mollusks (mainly green mussels) and crustaceans (mud crabs, lobsters and shrimps)

for a total of less than 1000 tons per year (FAOSTAT, 2019). The four above-mentioned grouping of fish and seafood products (namely the marine fishes, freshwater fishes, mollusks and crustaceans) require substantially different techniques to be produced, due to their intrinsic biological differences, and several aquaculture technologies exist for each of them. In Singapore, two production technologies were identified for marine fishes, and one for each of the three other seafood groups (SFA, 2019b). These technologies were differentiated into two types: the low technologies (termed “low-tech” in the following), which require limited energy inputs and low technical knowledge of the farmer, and the high technologies (termed “high-tech”), which demand more complex infrastructures, techniques and usually important financial investments. Combining the technology types with the seafood groupings led to identifying 5 categories of seafood-technology combinations in 2017 in Singapore, as displayed in Table 1 (columns 2 & 3).

Table 1: Different seafood-technology categories, representing Singapore’s aquaculture sector with their abbreviation.

	Low-tech (LT)	High-tech (HT)	Full RAS ^{a,b}	Offshore (OF) ^b
Marine fishes (MF)	MF-LT	MF-HT	MF-RAS^b	MF-OF^b
Freshwater fishes (FF)	FF-LT	-	FF-RAS^b	-
Crustaceans (CR)	-	CR-HT	-	-
Mollusks (MO)	MO-LT	-	-	-

^a Recirculating aquaculture system

^b Technology types and combinations with a potential for development in the future

In general, the fingerlings are imported from surrounding countries such as Malaysia or Indonesia. The feed, often commercial pellets, are imported too and usually originate from Vietnam or Thailand. Most of the marine fishes farmed in Singapore are omnivorous, while freshwater fishes are usually vegetarian. Sections 2.1.2-2.1.6 describe each of the 5 categories of seafood-technologies, using detailed information resulting from onsite data collection at farms and confirmed by communication with the Singapore Food Agency (SFA, 2019).

2.1.2 Marine fishes in “low-tech” systems

In marine fishes farms classified as “low-tech”, the juveniles are grown in fiberglass tanks on land, while the grow-out stage happens in open-sea nets attached to floating platforms made of wood and plastic. These farms typically use rainwater for their freshwater needs, have rather high feed conversion ratio (FCR) as their feeding management is not optimized and use cheap commercial feed pellets, sometimes not adapted specifically to the farmed species.

2.1.3 Marine fishes in “high-tech” systems

In “high-tech” farms, marine fishes’ juveniles are matured in recirculating water systems on land before being transferred to large cages in the open sea for the grow-out stage. In these farms, feed selection and feeding practices are usually based on deeper knowledge of the fishes needs and are therefore optimized, inducing carefully selected commercial pellets and lower FCR. Generally, fishes grown in these systems are harvested at bigger sizes than in “low-tech” and are of higher value due to the higher financial investments needed to run such a farm. Due to their sizes, they are not sold as entire fishes but gutted and filleted before being sold as fish fillets.

2.1.4 Freshwater fishes in “low-tech” systems

In Singapore, freshwater fishes are generally produced in “low-tech” farms, where the juveniles’ stage is similar to the marine fishes “low-tech” production, and the grow-out stage happens in ponds made of concrete and dug directly into the ground on land. They also use rainwater for their freshwater needs and have high FCR, but feed commonly stems from leftovers of surrounding food industries (e.g. chicken farms) to reduce their costs. The uneaten feed and dejections from the fishes form a sludge, which is extracted from the ponds during cleaning, and is then sold to local agriculture farms as manure.

2.1.5 Crustaceans in “high-tech” systems

Aquaculture production of crustaceans in Singapore is composed of approximately one third of small decapods (shrimps and prawns) and two third of large ones (lobsters, crabs and crayfish) (FAOSTAT, 2019). The two types require different technologies, but the production of crustaceans being very limited (around 200 tons in total in 2017 – FAOSTAT, 2019), it can be approximated as only one type of technology, referring to large decapods. These are usually produced in “high-tech” farms, where the crustaceans are grown in individual boxes disposed vertically and equipped with a recirculating water system. The feed is composed mainly of fresh fish and mollusks produced locally, as most species produced are carnivorous.

2.1.6 Mollusks in “low-tech” systems

The great majority of the mollusks produced in Singapore in 2017 are green mussels, farmed in “low-tech” systems. The mollusks are arranged on longlines and plastic barrels attached to floating platforms similar to those used for marine fishes in “low-tech” (made of wood and plastics). They are not fed, and nourish themselves with the nutrients available in the surrounding waters. Before being sold, the mollusks are cleaned to remove the seawater.

2.1.7 Future technology landscape

Based on the analysis of the literature regarding new trends in aquaculture and on personal communication with farmers and local authorities (SFA, 2019b), two additional future technologies of aquaculture were selected to be included in the analysis. The first one is full recirculating aquaculture systems (RAS), in which the whole growth of the fishes (juveniles and grow-out) happens in recirculating water systems. The water use is drastically reduced compared to other inland systems, offering opportunities for better nutrient management and better control of all parameters to e.g. accelerate the growth and reduce the FCR. The other considered future technology is offshore aquaculture, which is very similar to the “high-tech” farms described for marine fishes with the difference that the grow-out phase takes place in sea cages far away from the shore, thus implying a natural environment of high quality to enhance growth. Such systems also reduce the influence of the farms on each other, decreasing e.g. disease migration. Both marine and freshwater fishes can be produced in RAS, while only marine fishes can be produced in offshore systems. All these seafood-technologies combination groups are summarized in Table 1.

An important challenge of aquaculture is to reduce the impacts of its feed and its dependence on fisheries (Naylor et al., 2000). One way to decrease the dependence of aquaculture on wild capture is to substitute part of the fishes reduced to produce fishmeal and fish oil (FMFO) with by-products from the food industry. To anticipate possible mitigation of these impacts, another way is to replace the FMFO with other ingredients that have similar properties. We identified two novel feed ingredients that are likely to enter the composition of aquafeed in Singapore in the future: insect-based meal and algal oil. The former is promising as a replacement to fishmeal as insects are part of the fishes’ natural feed and they have been observed to have no significant influence on fish growth (Burr et al., 2012). The latter has the potential to replace fish oil as it has the same characteristics and similar Omega-3 content (Shah et al., 2017). Therefore, the two future feed options considered in this study are: (1) increasing share of the FMFO produced from fish by-products, and (2) changing part of the FMFO to insect-based meal and algal oil.

2.2 GOAL AND SCOPE DEFINITION

The goals of this LCA study are to: (i) produce life cycle inventories for the main aquaculture production systems, differentiated by technology type and species group, that are currently in use in Singapore as well as the ones with high potential of development in the future; (ii) compare these different production systems in term of environmental impacts for a set of 11 impact categories, in a present (2017) but also prospective (2040) approach; and (iii) highlight the stages of their life cycle which carry the highest environmental impacts and present environmental improvement potentials.

The functional unit is defined as “the average production of 1 ton of edible seafood for Singaporean households”. The system boundary, as illustrated in Figure 1, consists of five main elements, namely the fingerlings production (usually with a weight of ca. 1 g), the feed, the infrastructures (also including equipment), the consumables (e.g. oxygen and cleaning products) and the production stages (including energy and water usage, direct emissions happening during the production, and avoided products). For each of these elements, the whole life cycle is considered, from raw materials to end-of-life. For some technology types, fingerlings cannot be put directly in the grow-out environment and require a different setting until they reach a minimum weight of approximately 100 g, or the juvenile's growth step. In this situation, feed, infrastructures, consumables and production stages gather inputs and outputs linked to both the juvenile and grow-out steps.

Figure 1: System boundary of the aquaculture systems assessed in the study with all its life cycle elements (captured by large frame).

The study excludes harvesting (boats and fuel), cleaning of the cages/nets (usually via pressured water), boats manufacturing and materials, generators manufacturing and materials, transport of the materials to the farms (infrastructures) and post-farming processes other than gutting and filleting (i.e. transport to retailer, retailing, transport to consumer, cooking) due to lack of data on these steps and because they are considered negligible compared to the steps already included. The use of drugs, medicine and vaccines are also excluded. The edible portion is obtained by dividing the impacts of live-weight mass at farm gate by the edible ratio of the species group. The modeling uses an attributional modeling framework, according to the ILCD Handbook definition (EC, 2010). The software Simapro v9.0.0.49 was used to build and assess the model (PRé Consultants, 2018).

In this study, several processes of the feed production present multiple outputs that cannot be separated by subdividing the system. The ISO 14044 standards guidelines regarding handling of multifunctionality are followed to attribute impacts to the different functions produced: system expansion is prioritized with use of average data (consistent with attributional modeling; EC, 2010), then allocation based on physical characteristics and, if no other method is applicable, economic allocation (ISO, 2006a, 2006b). Co-products of wheat flour, rice bran and rapeseed oil production are all common human food or animal feed (Sharma, 2014) with no alternative conventional ways of production, so allocation based on the gross energy content is applied. Co-products of soybean meal is soybean oil, which is a highly valuable and used vegetable oil, so for the same reason than before, allocation based on the gross energy content is applied. Fishmeal and fish oil production are intrinsically linked, and both are highly valuable products that cannot be replaced, so again allocation based on the gross energy content is applied. During algal oil production, co-products that can be used as animal feed and light fuel are produced, and system expansion could be used with modelling of the conventional way of producing these. The sludge composed by uneaten feed and fish residues is typically used as a natural fertilizer, which avoids the production of synthetic fertilizers, therefore system expansion is used in that situation. Finally, the use of by-products from various industries (e.g. fisheries or chicken farms) as feed or inputs for feed manufacturing are considered with zero burden as they are considered as waste. The avoided waste management of those industrial by-products is neglected because of a total lack of data on their handling in Singapore.

2.3 BUILDING OF LIFE CYCLE INVENTORIES

2.3.1 Current situation (2017)

To build the life cycle inventories of the production systems currently existing in Singapore, primary data was collected in 13 farms using a reference questionnaire covering all parts of the system boundaries at farm level. Inventories of country-representative farms for each of the production categories were built by

averaging the data collected in individual farms relatively to their annual production. Whether a practice is common at the country level or corresponds to a specificity of one farm was determined based on expert knowledge. For confidentiality reasons, no specific species or farm names could be disclosed in this study, and only LCI data aggregated by seafood groups and technology types adapted to Singapore are provided herein. For simplification and standardization purposes, all feed products are modeled as originating from Vietnam and all fingerlings from Malaysia, which are the most common origin of these goods in Singapore. All FMFO are produced in Vietnam and plant-based ingredients in China, as they are the most important producers of these products in the region. Regarding the technologies that are not yet implemented in Singapore, life cycle inventories were built based on literature, namely Liu et al. (2016) for the RAS and García García et al. (2016) for the offshore system. It is assumed that the feed used in the new technology systems for marine fishes has the same composition as the one currently used in “high-tech” systems. Feed for freshwater fishes in RAS is based on literature (Rana et al., 2009). The FCR in the offshore system is assumed to be equal to the current “high-tech” system because the technology is not yet optimized. The nutrient emissions to water (for sea-based grow-out systems) and the production of natural fertilizers (for land-based grow-out systems) were calculated and modeled using the formula from Papatryphon et al. (2005), and it was assumed that 80% of the nutrients can be recovered and sold as fertilizer. The background system uses the Ecoinvent v3.5 consequential database, with some processes based on Agri-footprint v4.0 and remodeled using Ecoinvent for consistency (Durlinger et al., 2017; Wernet et al., 2016). The consequential database is used in order to prioritize system expansion, and the use of marginal data is considered negligible in the case of Singapore except for the electricity grid mix, which was remodeled using average grid mix data. The edible ratio, which is used to transform live-weight mass at farm gate to mass of edible seafood, varies across the different species groups as follows: marine fishes: 0.50, freshwater fishes: 0.40, mollusks: 0.48, and crustaceans: 0.20. In contrast to the other groups, marine fishes in “high-tech” and offshore systems are not sold as entire fish because fishes produced in these technologies usually amount to ca. 4-5 kg per fish. For these, gutting and filleting are included based on Winther et al. (2009), and trimmings are modeled with system expansion as avoided production of fish for FMFO reduction.

2.3.2 Prospective life cycle inventories (2040)

The prospective analysis based on the year 2040 implies necessary changes to the life cycle inventories built for the year 2017. Processes may evolve due to technical optimization, policies and/or societal changes. To reflect these changes, several parameters were varied in the LCIs over the period 2017-2040, as summarized in Table 2. Energy and water consumption at production level were decreased by a percentage of 10 to 20% depending on the level of maturity of the technology determined based on the expert knowledge of the authors. The FCR of each system was decreased following historical trends of the

species groups observed at global level since 2000 (Tacon and Metian, 2015), with the exception of marine fishes in “high-tech” systems, for which the FCR was decreased twice slower post-2017 than in the historical trend to reflect an already high degree of optimization (SFA, 2019). Finally, for Feed option 1 (see description in section 2.1.7), the proportion of by-products in the production of FMFO increased from 44% in 2017 to 80% in 2040. For Feed option 2, the freshwater and marine fishes in “low-tech” systems were not impacted because these systems are not expected to shift to these kinds of feed (SFA, 2019). Crustaceans' feed composition was not considered changed over time either because no literature was found assessing that such replacement was possible for this seafood type. For marine fishes in “high-tech”, RAS and offshore systems, a replacement of half of the FMFO by the other feed ingredients, including a part from plant-based meal, was applied. For freshwater fishes in RAS, all the fishmeal used is replaced by insect-based meal in 2040. This hypothesis was made based on the fact that freshwater fishes grown in Singapore are mainly catfish and Tilapia, which are vegetarian or omnivorous. The LCI for production of insect-based meal was built upon Thevenot et al. (2018), with a reduced electricity and water use to factor in technology optimization until 2040 and with a replacement of part of the feed by food waste, as inspired by Roffeis et al. (2017). The algal oil inventory was based on Passell et al. (2013). The electricity grid mix is expected to undergo only limited technological changes until 2040, with a vast majority of its production remaining sourced to gas; it was modeled using the changes anticipated by Asia Pacific Energy Research Centre (2016). A list of all references and detailed assumptions used to build the life cycle inventories is available in Table S1 and S2 of Supplementary Method.

Table 2: Processes and parameters undergoing a change between the 2017 and the 2040 life cycle inventories.

<i>Process/parameter</i>	<i>Change between 2017 and 2040</i>
Water consumption during production	Decrease by 10 to 20% depending on technology maturity.
Energy consumption during production	Decrease by 10 to 20% depending on technology maturity.
FCR	Decrease following historical trends of the period 2000-2015, except marine fishes in “high-tech” systems which decrease twice slower than historical trends because already high optimized.
Feed ingredients	Feed option 1: <ul style="list-style-type: none"> Part of FMFO produced from by-products increases from 44% in 2017 to 80% in 2040. Feed option 2: <ul style="list-style-type: none"> MFLT/FFLT/CRHT/MOLT: 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.
Electricity mix	Limited change (gas part is 93.9% in 2017 and 94.6% in 2040).

2.4 ASSESSED ENVIRONMENTAL IMPACT CATEGORIES

The impact assessment was conducted with life cycle impact assessment (LCIA) methods using indicators at midpoint level, hence defined along the cause-effect chain (EC, 2010). A total of 11 environmental impact categories were included, among which some commonly assessed in LCA studies and others more specific and relevant to aquaculture systems, as recommended by Bohnes and Laurent (2019) (see Table 3). For commonly assessed impact categories, the selection of LCIA methods was made to ensure comparability with previous LCA studies of aquaculture systems, wherever applicable (e.g. choice of CML; Guinée et al., 2001), or was based on up-to-date LCIA methodologies (e.g. IMPACT World+; Bulle et al., 2019) and recommendations from global guidance for life cycle impact assessment (UNEP SETAC, 2019, 2016).

Additionally, an impact specific to food production systems has been assessed, namely the net primary production use (NPPU). It is also a resource use impact category, which quantifies the amount of net primary production as a biotic resource that is not available for other systems anymore (Papatryphon et al., 2004), and is expressed in kg C. This impact is therefore linked exclusively to the feed use. For fish related ingredients, the NPPU was calculated using the formula from Pauly and Christensen (1995) which is: $NPPU = (M/9) * 10^{T-1}$, where M is the wet mass of the used organism and T is its trophic level. The average global mixture for FMFO production, which was assumed to be representative of the production in Vietnam, was used to calculate the NPPU of the FMFO used in this study (SEAFISH, 2018). For the plant-based ingredients, the NPPU was calculated based on the carbon content of the used crop (Papatryphon et al., 2004).

Table 3: Impact categories included in this study, with their associated indicators.

Impact category	Unit	Method / References	Description
Climate change short term	kg CO ₂ equivalent	IPCC GWP100a (Bulle et al., 2019)	Increase in radiative forcing caused by emissions of anthropogenic greenhouse gases. Based on Global Warming Potential for a 100-year time horizon.
Eutrophication	kg PO ₄ ³⁻ equivalent	CML-IA v3.05 (Guinée et al., 2001)	Impact on biodiversity from increasing nutrient concentration in water that may lead to decreased levels of oxygen, habitat loss, etc.
Acidification	kg SO ₂ equivalent	CML-IA v3.05 (Guinée et al., 2001)	Impact on biodiversity from decreased pH due to air deposition of acidifying substances
Land competition	m ² a	CML-IA v3.05 (Guinée et al., 2001)	Use of land expressed as surface during a year
Fossil and nuclear energy use	kg depleted	IMPACT World+ v1.26 (Bulle et al., 2019), same than the cumulative energy demand by Frischknecht et al. (2007)	Use of primary energy from fossil fuels and nuclear sources
Freshwater ecotoxicity	CTUe	USEtox v2.0 (Rosenbaum et al., 2008)	Toxicity exerted by chemical substances on freshwater ecosystems
Human toxicity cancer	CTUh	USEtox v2.0 (Rosenbaum et al., 2008)	Toxicity exerted by chemical substances on human health through different pathways (e.g. inhalation of air, ingestion of food and water). Carcinogenic effects.
Human toxicity non cancer	CTUh	USEtox v2.0 (Rosenbaum et al., 2008)	Toxicity exerted by chemical substances on human health through different pathways (e.g. inhalation of air, ingestion of food and water). Non-carcinogenic effects.
Mineral resource use	kg depleted	IMPACT World+ v1.26 (Bulle et al., 2019)	Fraction of material needed by future users that are not able to adapt to a full dissipation of the easily available stock
Water scarcity	world m ³ equivalent	Available Water Remaining (Boulay et al., 2018)	Remaining water available per area after human and aquatic ecosystem demand has been met, relative to the world average
Net primary production use	kg C	Method by Papatryphon et al. (2004)	Biotic resource that is not available for other systems anymore

3 RESULTS

The obtained LCIs are described in Section 3.1, and the results of the LCIA are presented in Section 3.2.

3.1 LIFE CYCLE INVENTORIES OF AQUACULTURE SYSTEMS IN SINGAPORE

The main input and output flows of all aquaculture systems under study are presented in Table 4. The detailed and complete life cycle inventories are available in the Supplementary Results spreadsheets. For confidentiality reasons, data collected in each individual farm could not be presented and all flows are aggregated per production type.

As visible in Table 4, aquaculture systems qualified as “low-tech” have an FCR approximately twice higher than “high-tech” ones, which have FCR slightly higher than the new technologies (i.e. RAS and offshore).

This illustrates the higher optimization of these technology types. Looking at electricity consumption, only crustaceans “high-tech”, freshwater fishes “low-tech” and the two RAS technologies use the electricity grid as supplier because their grow-out phase is on land. The other systems use power generators on sea platforms/cages for their electricity needs, and thus have an additional fuel consumption due to the use of boats to reach these platforms/cages. Fuel consumption for boats of the offshore system is approximately 4 times higher than the “high-tech” one, due to the fact that the distance from the shore is 4 times higher (see Section 2.1.7). Water consumption is null to very low for the “low-tech” systems, as they use mainly rainwater. The two full RAS have water needs comparable to the marine fishes in “high-tech” systems, which use a RAS only for the growth of juveniles (i.e. during half the total growth process), illustrating how highly optimized water usage is for the full RAS. Land occupation is particularly high for crustaceans’ culture, due to the use of individual boxes for each specimen, combined with a low edible factor for crustaceans (0.2 against 0.4-0.5 for the other seafood groups). Regarding infrastructures, most systems rely on concrete, and especially fishes “low-tech” systems due to their land-based ponds in concrete and the stabilizing blocks for their floating platforms. Full RAS systems primarily rely on fiberglass and sea cages systems made of steel and nylon. Finally, systems having a grow-out phase on land are further differentiated with regard to nutrient management. In these systems, the sludge containing the nutrients produced by the farm (i.e. uneaten feed and feces) is sold as natural manure to nearby agriculture farms, thus avoiding manufacturing of synthetic fertilizers, whereas for systems growing fishes in open sea these nutrients are emitted and therefore lost to the environment (where they can exert damages; see Section 3.2). This does not apply to mollusks, which feed on the nutrients already present in the open sea, and therefore remove nutrients from the water body during grow-out (hence the negative emissions reported in Table 4).

The feed composition in the two feed options (see section 2.3.2) is documented in Table 5. Feed composition for marine fishes “low-tech” and “high-tech” have a similar proportion of fishmeal, but a very different proportion of fish oil, with 16% for “high-tech” and only 1% for “low-tech”. This may be due to the price of fish oil, which is an expensive good, and to the fact that “low-tech” farms generally aim to reduce the costs wherever possible. In contrast, in “high-tech” farms, the quality and the fast growth of the fish are prioritized over the costs. There is an additional dependence on the specific species grown, as fishes grown in “high-tech” farms might require more fish oil to grow fast.

Table 4: Main inputs, emissions to water, avoided products and FCR of the 8 technologies and species of this study, based on the production of 1 ton of edible seafood (CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system).

	MF-LT	MF-HT	FF-LT	CR-HT	MO-LT	MF-OF	MF-RAS	FF-RAS
FCR in 2017	4.42	1.70	4.00	2.20	n.a.	1.70	1.50	1.50
FCR in 2040	3.96	1.46	4.00	1.69		1.22	1.02	1.02
Inputs (2017)								
Electricity (kWh)	-	-	155	23191	-	-	10920	13650
Fuel - generator (kg)	499	676	-	-	6.77	676	1.66	2.08
Fuel - boats (kg)	81	203	-	-	13	889	-	-
Water (m3)	0*	27.4	0*	30.3	0.2	27.4	23.4	29.2
Land occupation (m2a)	7	20	325	1250	21	20	27	33
Sea occupation (m2a)	241	39	-	-	694	20	-	-
Wood (m3)	1.2	-	-	-	17.4	-	-	-
Concrete (kg)	1673.5	25.2	9108.4	-	256.9	1.9	165.0	206.3
Steel (kg)	0.5	10.7	-	0.2	28.3	6.8	28.2	35.3
Cast Iron (kg)	-	-	-	-	-	3.4	-	-
PE (kg)	48.1	10.4	18.2	35.8	23.8	36.2	8.4	10.5
PP (kg)	-	-	-	-	11.4	9.4	-	-
PV (kg)	-	-	-	-	10.6	0.04	-	-
PS (kg)	-	1.0	-	-	0.7	0.5	-	-
PU (kg)	-	-	-	-	-	0.1	-	-
Nylon (kg)	3.6	2.3	-	-	-	8.2	-	-
Glass fiber (kg)	8.2	4.2	-	-	-	4.2	17.9	22.3
Cotton (kg)	-	-	-	-	0.7	-	-	-
Cleaning products (kg)	-	52	0.3	-	-	52	2.0	2.4
Ozone (kg)	-	5	-	0.01	-	5	-	-
Oxygen (kg)	-	900	-	-	-	900	1312.0	1640.0
Lime (kg)	-	-	-	-	-	-	438.0	547.5
Emissions to water								
Phosphorus (kg)	126	38	-	-	-0.7	39	-	-
Nitrogen (kg)	458	164	-	-	-9	174	-	-
Carbon (kg)	-	-	-	-	-182	-	-	-
Avoided products								
Fertilizer as P (kg)	-	-	71	10	-	-	30	38
Fertilizer as N (kg)	-	-	234	383	-	-	88	110

*: use of rain water.

Table 5: Composition of the different feed used in 2017 and 2040 (CR=Crustaceans; FF=Freshwater fishes; MF=Marine fishes)

Ingredients	MF ₁	MF ₂	MF _{future}	FF ₁	FF ₂	FF _{future}	CR
Used in...	MF-LT	MF-HT; MF-RAS; MF-OF	MF-HT; MF-RAS; MF-OF	FF-LT	FF-RAS	FF-RAS	CR-HT
Fishmeal	0.45	0.44	0.22	-	0.10	-	-
Fish oil	0.01	0.16	0.08	-	-	-	-
Soybean meal	0.10	0.29	0.35	-	0.44	0.44	-
Maize starch	0.04	0.11	0.11	-	0.14	0.14	-
Rice bran	0.03	-	-	-	-	-	-
Wheat bran	0.04	-	-	-	-	-	-
Wheat flour	0.08	-	-	-	-	-	-
Wheat middling	-	-	-	-	0.30	0.30	-
Rape oil	-	-	-	-	0.02	0.02	-
Fresh fish	0.13	-	-	-	-	-	0.70
Industry leftovers	0.13	-	-	1.00	-	-	0.30
Insect based meal	-	-	0.16	-	-	0.10	-
Algal oil	-	-	0.08	-	-	-	-

3.2 LIFE CYCLE IMPACT ASSESSMENT

The characterized impact assessment results for the 8 systems and the 11 impact categories are available in tabular format in Table S3 of Supplementary Results for both 2017 and 2040. In Section 3.2.1, the results of the comparisons between production categories are presented, and a hot-spot analysis for 2017 is thereafter conducted in Section 3.2.2. Finally, the results for 2040 are analyzed in Section 3.2.3 (comparison) and 3.2.4 (hot-spots).

3.2.1 Comparative results in 2017 across production categories

As visible in Figures 2 and 3, marine fishes in “low-tech” systems have the highest impacts for eutrophication, acidification, land competition and NPPU, while freshwater fishes in RAS present the highest impacts for climate change short term, water scarcity and human toxicity non cancer. Crustaceans have the highest impacts on mineral resource use, freshwater ecotoxicity, human toxicity cancer, and fossil and nuclear energy use. The lowest impacts are associated with freshwater fishes in “low-tech” systems for all 11 impact categories, among which 8 even have negative scores (i.e. positive impact on the environment). Indeed, as it is a closed system, the sludge composed of uneaten feed and feces is collected by the farmers and sold to local agriculture farms as natural fertilizer, avoiding therefore the production and use of synthetic fertilizer. Combined with the fact that to reduce costs, these farmers usually use coproducts from the food industry as feed, which is associated with no environmental impacts in this study because considered as waste, the total scores are negatives in most impact categories. Mollusks in “low-tech”

systems have the second lowest impacts in all impact categories except land competition because they are unfed organisms and therefore have no impacts due to feed production or consumption. Regarding the other production systems, crustaceans in “high-tech” systems show a mixed profile, as they have the third lowest environmental impacts in 4 impact categories (namely water scarcity, NPPU, human toxicity non cancer and climate change) but perform poorly in all other impacts assessed (see Figure 3).

Focusing on marine fishes, it seems that there is a larger variability with other species groups than within technology types. However, “high-tech” systems show interesting characteristics, embedding the lowest environmental impacts for acidification, climate change short term, net primary production, water scarcity, and fossil and nuclear energy use, and second lowest for this species group for the other impact categories. “Low-tech” systems (for marine fishes) have a contrasting profile, having the highest impacts in 7 out of 11 impact categories, but the lowest impacts for freshwater ecotoxicity and human toxicity cancer (see Figures 2 and 3). The RAS has the lowest impacts on human toxicity non cancer, land competition, mineral resource use and eutrophication among the marine fishes technologies, the latter being often considered as the most problematic environmental impact of aquaculture (Diana, 2009). A risk of burden-shifting between impact categories might thus occur when switching from existing technologies to the new ones, since the implementation of new technologies will most likely reduce impacts on eutrophication and NPPU while increasing toxicity impacts (for which new technologies perform generally poorly relative to others – see Figure 3). With these environmental trade-offs, it is therefore difficult to conclude on which technology should be preferred, even though the “high-tech” and the RAS systems seem to be the most beneficial in 2017.

Looking at climate change in particular, impacts per ton of edible seafood vary the most for freshwater fishes with -2.66 ton CO₂-eq for “low-tech” systems and 18.94 ton CO₂-eq for RAS. The negative number is due to the use of system expansion and the fact that the sludge composed by uneaten feed and feces is used as natural fertilizer hence avoiding the production of synthetic fertilizer. On the contrary, the production of marine fishes has a limited variation across technologies with 13.52 to 16.77 ton CO₂-eq/ton-edible-seafood. Finally, mollusks and crustaceans have 0.34 and 9.03 ton CO₂-eq/ton-edible-seafood respectively, therefore being lower than all fishes categories except freshwater fishes in “low-tech”.

Figure 2: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2017 for the 8 production systems under study (see Table 1). Graphs show differentiation between life cycle stages. CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system; NPPU=Net primary production use. Feed is the only contribution to NPPU impacts, hence NPPU results only show feed and post-farming distribution. LCIA methods used are documented in Table 3.

	<i>Acidification</i>	<i>Climate change, short term</i>	<i>Eutrophication</i>	<i>Freshwater ecotoxicity</i>	<i>Human toxicity cancer</i>	<i>Human toxicity non cancer</i>	<i>Land competition</i>	<i>Mineral resources use</i>	<i>Net primary production</i>	<i>Water scarcity</i>	<i>Fossil and nuclear energy use</i>	<i>Average 2017</i>	<i>Average 2040 Feed option 1</i>	<i>Average 2040 Feed option 2</i>
CR-HT												5.5	6.1	5.5
FF-LT												1.0	1.0	1.0
FF-RAS												6.5	6.5	5.6
MF-LT												6.2	6.3	5.2
MF-HT												4.2	4.4	5.7
MF-RAS												4.5	4.5	4.9
MF-OF												6.0	5.2	6.0
MO-LT												2.0	2.0	1.9

Figure 3: Ranking of the 8 technologies for the 11 assessed environmental impact indicators. Green cells indicate systems with lowest impacts and red those with highest impacts. The averaged rank over these 11 environmental impact indicators in 2017 and 2040 for Feed options 1 and 2 is shown in the last three columns (Feed option 1 = 80% of by-products in the production of fishmeal and fish oil; Feed option 2 = introduction of insect meal and algal oil in feed composition; CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system).

3.2.2 Contribution analysis in 2017

The detailed contribution analysis for the year 2017 is available in Table S3 of Supplementary Information, albeit some aspects are visible in Figure 2. As explained in Section 2.4, as feed is the only input to NPPU impacts, NPPU is not mentioned extensively in the contribution analysis.

Marine fishes. In general, feed production dominates the environmental impacts of marine fishes in all technology types. However, its importance decreases proportionally to the increase in technology optimization/innovativeness (with from the less to the more optimized: “low-tech”, “high-tech”, offshore and RAS). Indeed, the more optimized a technology is, the lower its associated FCR and the higher its energy and consumables need, generally. The most contributing ingredients vary depending on the impact category, but are in general fishmeal and soybean meal. In open systems, the production stage dominates eutrophication impacts due to nutrients emissions in open water during that stage, and fossil and nuclear energy use because of fuel consumption for the boats. For the RAS, production dominates freshwater

ecotoxicity and fossil and nuclear energy use because of the electricity consumption. Infrastructures are generally dominant for mineral resource use, but can also have an important contribution for land competition because of the use of wood for the construction of floating platforms (for the “low-tech” system). Except for “low-tech” systems, consumables are the main contributor to water scarcity and the human toxicity categories. Fingerlings’ production has a negligible contribution to all impact categories. Marine fishes in offshore sea cages show similar trends than marine fishes in “high-tech” systems, but with a more important contribution of the production stage. Indeed, the main difference between the two technologies is that the offshore system is 4 times farther from the coastline than the “high-tech” one and therefore impacts linked to the boats usage are proportionally higher. In general, a risk of burden-shifting between stages appears if going from the existing technologies to the new ones, as feed loses importance towards production and consumables (Figure 2 and SI).

Freshwater fishes. Freshwater fishes in “low-tech” systems have negative impact scores for all 11 impact categories except mineral resource use and land competition, due to the production of natural fertilizer and the thus-avoided production of synthetic fertilizer during production. Additionally, feed comes from farms by-products, considered as waste, and therefore has no impact. Mineral resource use and land competition are dominated by infrastructures because of the use of concrete for the ponds’ construction. Environmental impacts of freshwater fishes in RAS are similar to the ones of marine fishes in the same systems in terms of trends, but with slight changes due to different edible factors and feed composition, and therefore production of different amounts of natural fertilizer.

Crustaceans. Crustaceans in “high-tech” systems have a very different profile, as most impact categories are dominated by production stage because of electricity consumption. Feed dominates land competition and water scarcity due to the use of fresh fish as feed. Infrastructures dominate mineral resource use and human toxicity impacts due to the building construction. This seafood species requires a higher amount of fingerlings compared to the others. Therefore this stage dominates eutrophication through direct emissions of nutrients, as their production is assumed to take place in Malaysia where water is assumed to not be treated before being discharged to nature.

Mollusks. Environmental impacts of mollusks production are widely dominated by infrastructures, which is plausible as there are no consumables, no feed and no fingerlings inputs in this system. Infrastructures’ impacts are driven by the use of wood for the platform and the construction of the buildings for cleaning. Eutrophication presents a negative score because the mollusks are using nutrients from the environment as feed, therefore reducing nutrients content.

3.2.3 Comparative results in 2040

Some changes can be observed in the rankings across systems between 2017 and 2040 for the different impact categories (visible in last 3 columns of Figure 3). For Feed option 1, where a higher part of the FMFO is produced based on capture by-products (Figure 3), crustaceans in “high-tech” systems become in general worse than marine fishes in offshore systems. For Feed option 2, where insect meal and algal oil are introduced in the feed composition, the marine fishes in “high-tech” and in offshore systems become generally the two worst options, even though marine fishes in “low-tech” systems and crustaceans remain at a similar level (Figure 3). The two RAS are performing better than most of the other systems thanks to their lower FCR and hence the lower influence of feed on their impact results.

In general, Feed option 2 presents higher impacts than Feed option 1 (see Figure 4). For example in land competition, marine fishes have impacts 2.3 times higher in offshore systems for Feed option 2 than Feed option 1, and 7 times higher in RAS. NPPU impacts of marine fishes in “low-tech” systems are divided by 2.5 in Feed option 1 compared to Feed option 2. Moreover, impacts are generally decreasing with Feed option 2 and increasing with Feed option 1 compared to 2017 (see details in Section 3.2.4).

Climate change impacts decrease for all categories and all Feed options, even though not homogeneously, but the ranking within categories remain the same. In 2040, freshwater fishes have impacts between -2.66 and 16.67 ton CO₂-eq/ton-edible-seafood for “low-tech” and RAS respectively, while marine fishes have a lower variation range with only 11.25-14.59 ton CO₂-eq /ton-edible-seafood. Mollusks and crustaceans have impacts of 0.34 to 8.78 ton CO₂-eq /ton-edible-seafood respectively, being still lower than most fishes options for this impact category.

Figure 4: Characterized impact assessment results for the production of 1 ton of edible seafood in Singapore in 2040 for the 8 production systems under study (see Table 1). Graphs show differentiation between life cycle stages. CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system; NPPU=Net primary production use. LCIA methods used are documented in Table 3.

3.2.4 Evolution of each system through the years

“Low-tech” systems. For all technologies qualified as “low-tech”, minor changes are observed in terms of contributions between 2017 and 2040 because these are old technologies, which are not expected to change or increase during this period as they are already mature (see Table 5). The only noticeable change is NPPU for marine fishes, which decreases between 2017 and 2040 by 67% for the Feed option 1 and by 20% for the Feed option 2, because of the decrease in FCR (both Feed options) and the increase of by-product use in the manufacturing of FMFO (only Feed option 1).

Marine fishes. Impacts of marine fishes in “high-tech” systems, offshore systems and RAS have minor changes in terms of contributions in 2040 compared to 2017 for Feed option 1. NPPU indicator stands out as it decreases by 75-96% due to the increasing use of by-products in FMFO reduction (Table 5). The same hotspots as in 2017 are observed in this feed scenario. For Feed option 2, feed becomes dominant for most impact categories, due to the use of insect-based meal. Indeed, that ingredient has generally higher environmental impacts than fishmeal, despite its potential to reduce capture pressures. Its introduction induces an increase in most impact category scores between 2017 and 2040. Water scarcity is multiplied by 2.1-4.5 and land competition by 1.8-2.8. However, NPPU decreases by 79% thanks to the decreased use of FMFO (Table 5), again due to the introduction of insect-based meal in the feed composition. The dominant process of the insect-based meal production is the feeding the insects at insect farm level. For marine fishes in offshore systems, even though most impact category scores increase, impacts of eutrophication, climate change, NPPU, and fossil and nuclear energy use decrease by up to 87% (NPPU), due to a decrease of fuel consumption for the boat usage.

Freshwater fishes. In RAS, freshwater fishes have a similar profile than marine fishes grown with the same technology in the case of Feed option 1, but undertakes a less drastic change with Feed option 2 due to a lower use of insect-based meal. Only NPPU decreases notably by 88% as shown in Table 5.

Crustaceans. Changes in impacts of crustaceans are small between 2017 and 2040 (max +/-20%), except human toxicity non cancer which is multiplied by a factor of 6. This is due to a lower FCR in 2040 than 2017, which implies a lower production of natural fertilizer from the uneaten feed and feces, and finally a lower crediting from avoided production of synthetic fertilizer.

Species group Technology type Feed option	CR HT	FF LT	FF RAS 1	FF RAS 2	MF HT 1	MF HT 2	MF LT 1	MF LT 2	MF OF 1	MF OF 2	MF RAS 1	MF RAS 2	MO LT
Acidification	10%	-1%	-8%	1%	-16%	23%	-16%	-10%	-22%	5%	-15%	12%	0%
Climate change, short term	-3%	0%	-18%	-12%	-11%	-3%	-11%	-9%	-19%	-14%	-17%	-11%	0%
Eutrophication	10%	0%	-13%	0%	-16%	-13%	-14%	-14%	-34%	-32%	-10%	22%	0%
Freshwater ecotoxicity	7%	-2%	-2%	3%	-5%	70%	-7%	-6%	-12%	45%	-5%	21%	0%
Human toxicity cancer	4%	0%	-4%	1%	-7%	20%	-9%	-8%	-14%	5%	-8%	11%	0%
Human toxicity non cancer	494%	0%	-10%	7%	-9%	51%	-10%	-9%	-16%	28%	-4%	48%	0%
Land competition	-13%	-1%	-33%	8%	-13%	183%	-6%	-6%	-19%	89%	-40%	346%	0%
Mineral resources use	-2%	0%	-10%	12%	-6%	56%	-9%	-8%	-11%	37%	-2%	61%	0%
Net primary production use	-16%	n.a.	-70%	-88%	-90%	-79%	-67%	-20%	-96%	-87%	-75%	-68%	n.a.
Water scarcity	14%	0%	-15%	7%	-5%	114%	-10%	-10%	-8%	85%	-2%	80%	0%
Fossil and nuclear energy use	-9%	0%	-13%	-8%	-10%	7%	-10%	-8%	-15%	-5%	-14%	-4%	0%

Figure 5: Variation of the impact scores in 2040 compared to 2017 for the 8 systems, the 2 feed options and the 11 impact categories (1 (Feed option 1) = 80% of by-products in the production of fishmeal and fish oil; 2 (Feed option 2) = introduction of insect meal and algal oil in feed composition; CR=Crustaceans; FF=Freshwater fishes; MO=Mollusks; MF=Marine fishes; RAS=Recirculating aquaculture system; OF=Offshore system; LT= “Low-tech” system; HT= “High-tech” system; “n.a.” = not applicable). Green and red cells indicate impact decreases and increases, respectively.

3.3 SENSITIVITY ANALYSIS

Building on the contribution analyses carried out in Section 3.2, a sensitivity analysis was conducted to assess the influence of some key parameters and modeling choices on the results. For this purpose, the FCR, the boats usage of the offshore system, the electricity consumption of the RAS and the proportion of the feed for insect production originating from by-products were varied by +/-10%. An important methodological choice was additionally tested: the by-products of chicken production used as feed for the freshwater fishes in “low-tech” systems, which was remodeled as a co-product of chicken production (instead of waste). Gross energy allocation was applied to handle the multifunctionality of chicken production. Finally, other LCIA methods were tested, with the alternative use of ReCiPe 2016 Midpoint, which include generally the same impact categories as listed in Table 3, but with different indicator definitions and characterization models for calculating impact indicator scores (Huijbregts et al., 2016). All the sensitivity analyses are summarized in Table 6 and their detailed results are available in Table S4 and S5 of Supplementary Information. A synthesis of key findings is reported below.

FCR influence. Varying the FCR by +/-10% had a large influence of the results for all systems, which have a non-null feed input (i.e. all except freshwater fishes and mollusks in “low-tech” systems). Impact scores

varied on average by $\pm 2.8\%$ (crustaceans in “high-tech” systems in 2040) to $\pm 11.7\%$ (marine fishes in offshore systems with Feed option 1 in 2040). In general, NPPU, eutrophication, land competition and water scarcity are the impact categories the most impacted by the change of FCR.

Use of boats in off-shore systems. Variation of the use of boats in offshore systems by $\pm 10\%$ was found to have a moderate influence on the results. While land competition varies by $\pm 4.6\%$ in 2040 for Feed option 1, it varies only by $\pm 2.0\%$ with Feed option 2. This is due to the increased importance of feed compared to production stage with option 2. Fossil and nuclear energy use vary by ± 2.8 to $\pm 3.2\%$ depending on the year and the Feed option. The other impact categories have a variation lower than $\pm 3.0\%$.

Electricity usage in RAS. This parameter was found to have a large influence on the results. Freshwater ecotoxicity and fossil and nuclear energy use vary by around $\pm 6\%$, and acidification and climate change by approximately $\pm 4\%$ for marine fishes but only $\pm 3\%$ for freshwater fishes. This is due to the higher contribution of feed for freshwater fishes compared to marine ones. The other impact categories vary by less than 3% .

Feed input in insect farming. Varying the feed input during insect farming by $\pm 10\%$ resulted in a low influence on the results except for land competition and water scarcity. For the former, the impact score for marine fishes in RAS with Feed option 2 varies by $\pm 8.6\%$. For the latter, the score for marine fishes in “high-tech” systems fluctuates by $\pm 4.1\%$.

Co-product from chicken production. Accounting for the feed given to the freshwater fishes as a co-product from chicken production resulted in a large influence on the results. This production category shifts from having the lowest environmental impacts in all impact categories to having the highest, except for NPPU and water scarcity. This is due to a high environmental impact of poultry production in general, combined with a high FCR for this system (i.e. ratio of 4). Therefore, whether the chicken leftovers are usually used as animal feed or not is a crucial question for the results of freshwater fish production. In Singapore, it is indeed more likely that the leftovers would be thrown away as the food production is very low in general. However, in other countries where chicken leftovers are in general used for feeding other animals, the environmental benefits of this particular feed source could be much reduced.

Change of LCIA methods. Changing the impact assessment methodology for ReCiPe 2016 affects the results moderately. The rankings are generally the same. Freshwater fishes and mollusks in “low-tech” systems still have the lowest impacts in all impact categories. In 2017, marine fishes in “low-tech” systems have the highest impact scores for 5 impact categories (i.e. particulate matter formation, marine eutrophication, ozone formation, stratospheric ozone depletion, terrestrial acidification and terrestrial ecotoxicity),

crustaceans in “high-tech” systems in 5 impact categories (i.e. fossil resource scarcity, freshwater ecotoxicity, human carcinogenic toxicity, marine ecotoxicity, mineral resource scarcity) and RAS in 5 categories (i.e. global warming, ionizing radiation, land use, water consumption and human non-carcinogenic toxicity). Therefore, it seems that marine fishes in “low-tech” perform less poorly, to the disadvantage of crustaceans in “high-tech”. The variation between 2017 and 2040 is usually small, like with the original set of LCIA methods. Ionizing radiation impacts, which are not included in the main study, are the highest by far in the RAS and are dominated by the consumables.

Table 6: Sensitivity analysis conducted in this study, with the parameters that were changed and their variation or new hypothesis.

Parameters	Variation/New hypothesis	Influence
FCR	+/-10%	High
Electricity need for the 2 RAS	+/-10%	High
Fuel needs of the boats for the offshore system	+/-10%	Moderate
Proportion of the insects’ feed coming from waste	+/-10%	Moderate
Feed for freshwater fishes in “low-tech” systems	By-product of chicken production (instead of waste)	Very high
Life cycle impact assessment method	ReCiPe 2016 Midpoint	Low

4 DISCUSSION

4.1 COMPARISONS WITH PREVIOUS AQUACULTURE LCA STUDIES

According to Bohnes and Laurent (2019) who reviewed 65 papers doing LCAs of aquaculture production systems, most past studies chose a functional unit based on live-weight, i.e. they were cradle to farm-gate analyses. In this study, we considered the production of an edible mass of seafood to allow a more realistic comparison of different seafood groups that have a different edible ratio. Therefore, to compare our results with past LCA studies, results using a secondary functional unit based on live-weight mass were computed. According to a sequel paper of the same review (Bohnes et al., 2019), the previous studies overall found climate change impacts between -0.2 and 31.4 tons CO₂-eq per ton of live-weight seafood. In this study, the climate change impacts vary between -1 to 8 tons CO₂-eq per ton of live-weight seafood, which is therefore consistent. In both cases, the upper bound of the range corresponds to RAS.

Regarding eutrophication, past studies fall within a range of -31 to 1410 kg PO_4^{3-} -eq per ton of live-weight seafood (Bohnes et al., 2019) while the current study reported results ranging between -2.5 and 96 kg PO_4^{3-} -eq per ton of live-weight seafood. The upper bound in the existing body of past studies is therefore approx. 10 times higher than the current study, and corresponds to a polyculture pond system in China that does not utilize the high-content nutrient sludge as natural fertilizer, explaining the high eutrophication impacts. For acidification, the range in past studies varies from 0.3 to 260 kg SO_2 -eq per ton of live-weight seafood whereas it ranges from -3 to 32 kg SO_2 -eq in the current study (Bohnes et al., 2019). Interestingly, the upper bound in past studies as well as in the current one corresponds to pond systems.

Past studies found scores in the range 1.7-353 GJ deprived when assessing the cumulative energy demand (Bohnes et al., 2019), which uses the same methodology than the fossil and nuclear energy use from the current study, in which a range was found to be -5 to 89 GJ deprived. The score of 353 GJ deprived is associated to a RAS, similarly to our study for the upper bound of 89 GJ deprived. This could be explained by a higher level of optimization of the system assessed in this study. Finally, regarding NPPU, past studies have found scores from 0.1 to 233 tons C per ton of live-weight seafood while this study found scores between 0 and 50 tons C per ton of live-weight seafood (Bohnes et al., 2019). The upper bound in previous studies stems from a nets system in the sea, similar to the system showing the highest impacts in the current study for this impact category.

Even though the different methodological choices were not harmonized between studies (e.g. use of allocation vs. system expansion, the latter of which explains negative impact assessment results), the impact indicator scores of the current study overall are consistent with the ranges of results obtained for different impact categories in the past studies. In addition to positioning the performances of the production systems in Singapore, this finding attests of the overall validity of the study and its background data.

4.2 CURRENT VS. NOVEL TECHNOLOGIES

The impact assessment results need to be put in perspective with the potential of each system to increase its production in Singapore. Freshwater fishes in “low-tech” systems have the lowest environmental impacts in all impact categories (see Figures 2 to 4), but it would be difficult to increase production from this type of system in Singapore. First, these systems require 325 m^2a of land per ton of edible seafood at production stage according to the life cycle inventory, which is at least 10 times more than any other system except crustaceans (Table 4). This is not reflected in the final scores for land competition since this category is largely dominated by the feed production, which occurs outside Singapore, and the LCIA method for assessing land use used in this study does not reflect land scarcity (i.e. 1 m^2a of land has similar impact wherever in the world). Furthermore, the low environmental impacts of this option are due to the

combination of the feed origin (food industry by-products, therefore associated to no impacts), and the assumption that the produced nutrient sludge is used as natural fertilizer (replacing the production of synthetic fertilizer, therefore associated with negative impacts). However, both would be challenged if the production increases. Indeed, Singapore is a small island and its food production is much limited. There is therefore a limited amount of leftovers from industry available for use as fish feed, and there is a limited amount of agriculture farms that could theoretically use the sludge as natural fertilizer. If normal feed pellets were used instead of the industry leftovers, like it is done (and modeled) for the other systems, this system's impacts would increase significantly due to its high FCR. Similarly, if the sludge cannot be used as fertilizer and needs to be treated as waste, all the offset of this technology would likely disappear. Production of large crustaceans in boxes faces the same issues in term of development potential, as it requires more than 1000 m²a of land for the grow-out stage per ton of edible seafood produced and its main advantage is the potential offset of synthetic fertilizers (Table 4), of which the demand is very limited in Singapore due to the extremely low amount of agriculture farms in the country, and unlikely to increase drastically because such production requires large land areas in general. Likewise, the culture of mollusks in “low-tech” systems has important limiting factors, which would prevent its large scale development in Singapore as well. Mollusks feed on the surrounding nutrients, which makes them highly dependent on the water quality in terms of nutrient content. Mollusks are also particularly vulnerable to predator species, as they are small in size and can hardly be protected by nets. As an illustration of this, Singapore used to produce up to 5900 tons of green mussels per year in the mid-2000s, but its production collapsed drastically since then because of an algae invasion in the farms around 2007 and stagnates now around 500 tons per year (SFA, 2019b).

In contrast to the other production categories, marine fishes produced in “high-tech” and offshore systems have a particularly high development potential in Singapore, as these technologies require little land space (SFA, 2019b). The main barrier for a radical increase of production in “high-tech” systems is the risk of rising eutrophication in coastal areas, which would be avoided with offshore systems as they are farther away from the coast. This difference is currently not accounted for in the eutrophication impact category, as it does not include any spatial differentiation. Even in newer LCIA methods that do include some spatial differentiation, the accuracy is not high enough to reflect such differences due to a lack of comprehensive data on eutrophication potential of the different zones. Paradoxically, environmental impacts of offshore systems were generally found to be higher than the “high-tech” system (Figures 2 to 4) because of the higher fuel consumption due to the longer distances traveled by the vessels to/from the coast. It is possible to decrease fuel use by making less trips to the cages (e.g. use of automatic feeder, cameras, detection systems) or by using less polluting boats (e.g. electric boats, low consumption boats). Similarly, there is a high potential of increasing RAS production in Singapore as it could be built in or on buildings, on rooftops or even vertically (urban aquaculture - Tan, 2019), and its environmental impacts are among the lowest of

the current study for both Feed options in 2040 (Figure 4). New farms could additionally decrease their impacts by decreasing their electricity consumption from the grid thanks to the installations of photovoltaic systems on the farms, or by reducing the oxygen usage through process optimization. Impacts of freshwater fishes in RAS were found to be mainly dominated by feed due to the use of soybean as primary input, which could be replaced by other ingredients.

Thus, an environmental trade-off is expected between systems having important impacts in terms of eutrophication and those requiring important areas of land during the grow-out stage. The former category includes marine fishes in “low-tech”, “high-tech” and offshore, whereas the latter includes freshwater fishes in “low-tech”, crustaceans in “high-tech” and both RAS. Overall, a combination of marine fishes in “high-tech” and RAS appears as a better compromise for Singapore, as their eutrophication impacts are considerably lower than in the “low-tech” systems and they have low land use impacts during the grow-out phase.

4.3 CONVENTIONAL VS. INNOVATIVE FEED INGREDIENTS

The Feed option involving the introduction of novel ingredients have been found to generally increase the impacts rather than decreasing them, except for NPPU (see Figure 4). Generally increasing the proportion of the FMFO produced via trimmings is more interesting from an environmental point of view than replacing FMFO by insect-based meal and algal oil. Insect-based meal has higher environmental impacts than fishmeal and soybean meal for most impact categories, which induced an increase of the impacts for Feed option 2. The production of insect-based meal was optimized in the model to reflect a production occurring in 2040, but the optimization potential may be higher than what was modeled (i.e. decrease by 20% of the water and energy consumption and by 50% of the feed consumption compared to the original LCI for 2017 - Thevenot et al., 2018). For example, some insects can potentially be fed with 100% of by-products and waste (Roffeis et al., 2017), which was not considered here. Nonetheless, an important benefit of using insect-based feed is the reduced pressure on fish stocks while keeping natural diets for the fishes, but this is reflected only through NPPU in the current study. Replacing fish oil by algal oil thus showed some benefits, partly due to the production of by-product having functions similar to animal feed and light fuel. Moreover, the manufacturing of the oil has important electricity needs which could be reduced by optimizing the production or use of more environmental-friendly electricity sources, and hence would contribute to reducing the impacts of algal oil.

Regardless of the type of feed ingredients chosen by the farmer, these need to be imported to Singapore since the domestic production of feed is near inexistent (FISHSTAT, 2018). “Low-tech” productions have in general a higher FCR (Table 2), implying higher needs of feeds imports. This suggests a potential transfer

of the imports of seafood for human consumption to imports of animal feed. As the main goal of the new Singaporean government's aquaculture policy is to decrease its reliance on imports by increasing local production (Zulkifli, 2019), the systems with the lowest FCR should be preferred. In general, RAS are the systems with the lowest FCR, but they have shown to have high energy and consumables requirements, which are the source of most environmental impacts. Therefore, a second important trade-off can be identified: the risk of switching from production systems having high feed requirements to those associated with high energy and consumables requirements. Electricity supply is not an issue in Singapore because the country is a net exporter (Asia Pacific Energy Research Centre, 2016b). However, electricity production in Singapore is mainly based on natural gas (and anticipated to remain the main energy source in the future; Asia Pacific Energy Research Centre, 2016), which is imported since Singapore does not have domestic production. Therefore, while switching the production from systems with high input of feed to systems with high inputs of energy/consumables, the increased aquaculture production in Singapore may result in an increase in imports of other goods than food.

4.4 UNCERTAINTIES AND LIMITATIONS

Despite being consistent with the results from past LCA studies in the field, this study carries some limitations, which need to be considered when analyzing the results and drawing conclusions. First of all, there is high uncertainty – albeit difficult to gauge – regarding the modeling of technologies that do not yet exist in Singapore. The developed life cycle inventories were inspired by existing LCA studies and adapted to the present case, but it is possible in the future that RAS and offshore systems in Singapore may be implemented in a different way from the ones modeled in our study. Similarly, the “future” ingredients inventories are based on scientific literature and their hypothetical production in China based on expert knowledge from the authors. In light of the above source of uncertainties, the results for the year 2040 should be analyzed by looking at the trends from 2017 rather than focusing on the specific absolute impact scores.

Another limitation of this study is linked to the impact assessment choices. Only 11 impacts categories are included, and only indicators at midpoint level are considered. Therefore, some impacts such as particulate matter formation or ionizing radiation, both impacting human health, are not assessed, and their potential inclusion may influence the conclusions. However, we included NPPU, which is not commonly part of impact assessment in LCA. This indicator mainly aims to reflect the specific impacts of using different feed ingredients as a resource, as no other commonly-assessed impact category covers that aspect. It thus indirectly reflects the depletion of fish stocks. It has been included in several other aquaculture and agriculture LCA studies, although its ability to measure comprehensively the targeted issue of marine resources depletion can be questioned (Langlois et al., 2014). Another impact category reflecting the use

of fish from capture is the maximum sustainable yield developed by Emanuelsson et al. (2014), but the method is limited to the wild capture and therefore does not reflect the use of non-marine ingredients. Other studies have used the human-edible protein conversion efficiency as an additional indicator to assess the use of feed in aquaculture and agriculture (Wiedemann et al., 2015). However, categorizing proteins as edible or non-edible by humans is subjective, making this indicator complex and very uncertain to analyze. Therefore, we recommend to keep using the NPPU indicator and to integrate systematically in future aquaculture studies, although it should be improved by building a reference LCIA method with characterization factors for the main commonly used ingredients, including, but not limited to, FMFO from the leading production countries, wheat flour and soybean meal.

5 CONCLUSIONS & RECOMMENDATIONS

Comprehensive LCIs of 8 categories of aquaculture production for four species groups have been constructed for Singapore, and developed for both 2017 and 2040. This provision of LCIs for several production systems and species can be regarded as a major step in enabling the future conduct of more aquaculture LCA studies in Asia. A comparative LCA of the eight aquaculture production systems was conducted in Singapore, including existing and potential future production systems, to generate a prospective analysis of the environmental impacts of different seafood production in that country. Such a study is therefore one of the first prospective LCA studies in the field of seafood production.

Overall, per unit of edible seafood produced, the production of marine fishes in RAS and in sea cages near the shore are found to be the most interesting options to limit the environmental impacts while increasing the production in Singapore. Despite having the lowest impact indicator scores per ton of edible seafood produced, the environmental impacts of freshwater fishes in concrete ponds are highly sensitive to methodological choices and this production category has a limited potential to increase its production capacity in the future due to its dependence on external factors, like land space availability. Increasing the part of FMFO produced based on trimmings is found to have more environmental benefits than replacing FMFO by insect-based meal and algal oil. However, the uncertainty concerning the future technologies is high, and to allow for a more refined assessment of the potential environmental impacts of the future increase in aquaculture production, more studies should be conducted on novel technologies and feed options that are specifically adapted to Singapore. Until these become available, environmental impact assessments of the new aquaculture farms and pilot plants while still under development can help foresee and prevent new potential environmental issues and contribute to the mitigation of existing ones.

This study adds on to the few numbers of LCA studies carried on Asian aquaculture systems, which yet represent the largest proportion of the global seafood production. This provision of LCIs for several

production systems and species in our study can be regarded as a major step in enabling the future conduct of more aquaculture LCA studies in Asia. Yet, there is still a need for an increased focus on Asian aquaculture and, along with it, the building of new LCIs. These LCIs along with the ones provided in the current study should be integrated into commonly used databases such as Ecoinvent (Wernet et al., 2016) to enable wider use by LCA practitioners and environmental analysts. Finally, this study limits its analysis to individual technologies and species groups without placing them in a broader national context, particularly without considering potential aquaculture and/or food policy planning and implementations. Such analysis in a wide perspective is however needed to support policy-makers in decisions related to environmental sustainability and thus help them in the selection of the most environmentally-friendly aquaculture production pathways/solutions.

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SUPPLEMENTARY INFORMATION A

Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore

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TABLE OF CONTENTS

Abbreviations	2
Supplementary methods	3
Supplementary results	7
Supplementary references	25

ABBREVIATIONS

MFLT	Marine fishes in « low-tech » systems
MFHT	Marine fishes in « high-tech » systems
MFOF	Marine fishes in offshore systems
MFRAS	Marine fishes in recirculating aquaculture systems
FFLT	Freshwater fishes in « low-tech » systems
FFRAS	Freshwater fishes in recirculating aquaculture systems
CRHT	Crustaceans in « high-tech » systems
MOLT	Mollusks in « low-tech » systems
NPPU	Net primary production use
FMFO	Fishmeal and fish oil
FCR	Feed conversion ratio

SUPPLEMENTARY METHODS

Table S1: References and hypothesis used to build the life cycle inventories.

Process	Source	Main hypothesis
Mealworm larvae production	Thevenot et al. (2018)	
Algal oil production	(Passell et al. 2013)	System expansion for the co-products (oil cakes and low value lipids)
Soybean meal	Based on Ecoinvent process	Gross energy allocation
Soybean oil		
Maize starch	Based on Ecoinvent process	
Wheat flour		
Wheat bran	Based on Agri-footprint process	Gross energy allocation
Wheat middling		
Wheat gluten		
Rice bran	Based on Agri-footprint process	Gross energy allocation with white rice, rice husks and rice broken
Rape oil	Based on Ecoinvent process	Gross energy allocation with rapeseed meal
Sunflower meal	Based on Agri-footprint process	Gross energy allocation with sunflower oil
Landed fish for fishmeal and fish oil	Based on Ecoinvent process (Landed anchovy)	
Fishmeal	Based on Ecoinvent process (Fishmeal, 65-67% protein, from anchovy)	Gross energy allocation
Fish oil		
Feed pellets production	(Samuel-Fitwi et al. 2013)	
Feed for freshwater fishes in RAS	(Rana et al. 2009)	
Fingerlings production	(Medeiros et al. 2017)	
Survival rate for freshwater fish fingerlings	(Olanrewaju et al. 2016)	
Floating platforms	(Baliao et al. 2000)	Extrapolated based on active surface
Marines cages	(Ayer et al. 2016)	
RAS production	(Liu et al. 2016)	
Survival rate of fingerlings in RAS nursery	(Summerfelt et al. 2013)	
Offshore aquaculture	(García García et al. 2016)	
Mollusks production	(Lourguioui et al. 2017)	
Boat consumption and emissions	https://www.oxe-diesel.com/About-Oxe/Emissions/CO2de	
Diesel generator consumption and emissions	(De Oliveira et al. 2015)	
Calculation of N and P emissions from production	(Papatriphon et al. 2005)	
Mussels nutrients needs and emissions during grow-out	(Brigolin et al. 2009)	
Net primary production use	(Papatriphon et al. 2004) (Pauly and Christensen 1995)	
Phosphorus and protein content for land-based ingredients	https://www.feedtables.com/content/	

Protein digestibility for marine fish	(Riche et al. 2017)
Protein digestibility for freshwater fish	(KHAN 1994)
Edible yield of marine fishes	http://www.fao.org/3/T0219E/T0219E01.htm
Edible yield of freshwater fishes (expected to be mainly Tilapia and Catfish)	(Jankowska et al. 2007) and (Garduño-Lugo et al. 2003)
Edible yield of crustaceans (expected to be mainly crabs)	(US.FOODS 2018)
Edible yields of mussels	(Rivonker et al. 1993)
Slaughtering and gutting of marine fishes	(Winther et al. 2009)
Fileting of marine fishes	(Silvenius and Grönroos 2003)

List of main assumptions:

Feed

- All marine ingredients are produced in Vietnam (closer important producer).
- All other ingredients (mainly cereals, but also insect-based meal and algal oil) are produced in China (closer important producer).
- All feed pellets are produced in Vietnam (closer important producer).
- Transport of the ingredients to pellets factory is 1500 km by truck from China and 200 km by truck from Vietnam.
- Transport of feed from Vietnam is 1500 km by sea and 200 km by road.
- Feed composition for marine fishes produced for future technologies is similar to the one used for marine fishes produced in “high-tech” system.

Fingerlings

- All fingerlings originate from Malaysia.
- Fingerlings are transported by ships from Malaysia over 1500 km and by truck over 200 km.
- Weight of fingerlings when arriving to the farm is 1 g.

Production

- General
 - Occupational time of all farms is 50 years.
 - For each category, equal weight is attributed to all farms visited because it is assumed that they are all equally representative.
 - RAS clean the water "perfectly" and there is not waste in the discharged water.
 - In all RAS, the wastewater is equal to half the input water (because of evaporation).
 - In closed systems, 80% of the nutrients produced can be used as fertilizer.
- Marine fishes in “low-tech”, or marine nets
 - For the fingerling growth step, only infrastructures and feed are considered because of lack of information on the rest.
 - Half of the surface on-land is covered by building.
 - There are 50% more nets than pools.
 - Weight of a 20 L plastic container is 1 kg.
 - Thickness of the rearing tanks is 3 cm.
 - Width of the wooden floor is 10 cm.
 - Lifetime of marine nets is 5 years.
 - Density of the nets is 0.13 g/m².
 - Lifetime of other infrastructures is 20 years.

- Average weight of fish produced is 700 g.
- Marine fishes in “high-tech” systems, or marine cages
 - Half of the surface on-land is covered by building.
 - Lifetime of nets is 5 years.
 - Lifetime of RAS system is 10 years.
 - Lifetime of the rearing tanks is 20 years.
 - Thickness of the rearing tanks is 3 cm, diameter is 3 m, depth is 1.2 m and amount is 20 pieces.
 - RAS is constituted by 1000 m of pipes, 500 kg of plastic and 100 kg of concrete.
 - Average weight of fish produced is 4.5 kg.
- Freshwater fishes in “low-tech” systems, or concrete ponds
 - Motors used to make the water circulate are neglected.
 - Lifetime of the ponds is 20 years.
 - Thickness of concrete for the ponds is 30 cm.
 - Depth of the ponds is 2 m.
 - Average length of water pipes bringing water to a pond is 130 m, and there is an average of 4 pipes per pond.
 - Average weight of fish produced is 500 g.
- Marine fishes in RAS
 - All surface on land is covered by buildings.
 - Average weight of fish produced is 700 g.
- Marine in offshore systems
 - Half of the surface on-land is covered by building.
 - FCR in 2017 is equal to the one of marine fishes in “high-tech”, but uneaten feed proportion is higher (20%).
 - Average weight of fish produced is 4.5 kg.
- Freshwater fishes in RAS
 - All surface on land is covered by buildings.
 - Average weight of fish produced is 500 g.
- Crustaceans in “high-tech” systems
 - A quarter of the on land area is covered by building.
 - Lifetime of the boxes is 5 years.
 - Lifetime of the RAS is 10 years.
 - Recirculation rate of the RAS is 4 times a day.
 - Boxes are 2 cm thick with a permanent 5 cm water in it.
 - The RAS has 500 m of pipes, 100 kg of plastic and 10 kg of steel.
- Mollusks in “low-tech” systems
 - The nutrients cycle is similar to blue mussels on Baltic Sea.
 - All the on land area is covered by a constructed hall.
 - A quarter of the area at sea is covered with the wooden platform.
 - The platform has the same characteristics than the one for marine fishes in “low-tech”
 - Mussels’ larvae are handpicked in Singapore and are therefore not imported from Malaysia.

Table S2: Technology maturity and corresponding decrease of water and energy consumption between 2017 and 2040

Category	Degree of maturity	Decrease in input within 2017-2040
MFLT	Mature	5%
MFHT	Improving	10%
MFOF	New	15%
MFRAS	New	15%
FFLT	Aging	0%
FFRAS	New	15%
CRHT	Improving	10%
MOLT	Aging	0%

SUPPLEMENTARY RESULTS

Table S3: Characterized results for the 11 impact categories, the 8 production systems and the 2 feed options. Differentiated by life cycle elements.

		Consumables	Feed	Fingerlings	Infrastructures	Production	Post-farming	Total
Acidification								
	2017							
CRHT		3.51E-04	2.36E+00	7.03E-01	1.62E+01	3.43E+01	0.00E+00	5.36E+01
FFLT		2.42E-03	1.39E-01	1.22E-02	3.37E+00	-1.11E+01	0.00E+00	-7.56E+00
FFRAS		1.23E+01	1.77E+01	8.93E-03	6.13E-01	2.65E+01	0.00E+00	5.71E+01
MFHT		7.10E+00	2.68E+01	9.80E-04	8.02E-01	1.43E+01	1.32E+00	5.03E+01
MFLT		0.00E+00	5.35E+01	1.67E-02	2.07E+00	1.58E+01	0.00E+00	7.13E+01
MFOF		7.10E+00	2.68E+01	9.80E-04	1.44E+00	2.50E+01	1.32E+00	6.16E+01
MFRAS		9.87E+00	2.36E+01	5.09E-03	4.90E-01	1.97E+01	0.00E+00	5.37E+01
MOLT		0.00E+00	0.00E+00	0.00E+00	3.98E-01	2.95E-01	0.00E+00	6.93E-01
	2040							
CRHT		3.51E-04	1.97E+00	1.46E+00	1.62E+01	3.94E+01	0.00E+00	5.90E+01
FFLT		2.42E-03	1.39E-01	2.53E-02	3.37E+00	-1.10E+01	0.00E+00	-7.50E+00
FFRAS1		1.23E+01	1.19E+01	1.85E-02	6.13E-01	2.79E+01	0.00E+00	5.28E+01
FFRAS2		1.23E+01	1.63E+01	1.85E-02	6.13E-01	2.82E+01	0.00E+00	5.74E+01
MFHT1		7.10E+00	2.00E+01	2.03E-03	8.02E-01	1.29E+01	1.65E+00	4.25E+01
MFHT2		7.10E+00	3.96E+01	2.03E-03	8.02E-01	1.29E+01	1.65E+00	6.21E+01
MFLT1		0.00E+00	4.28E+01	3.47E-02	2.07E+00	1.50E+01	0.00E+00	5.99E+01
MFLT2		0.00E+00	4.75E+01	3.47E-02	2.07E+00	1.50E+01	0.00E+00	6.46E+01
MFOF1		7.10E+00	1.68E+01	2.03E-03	1.44E+00	2.12E+01	1.65E+00	4.82E+01
MFOF2		7.10E+00	3.32E+01	2.03E-03	1.44E+00	2.12E+01	1.65E+00	6.46E+01
MFRAS1		9.87E+00	1.40E+01	1.06E-02	4.90E-01	2.13E+01	0.00E+00	4.57E+01
MFRAS2		9.87E+00	2.78E+01	1.06E-02	4.90E-01	2.18E+01	0.00E+00	6.00E+01
MOLT		0.00E+00	0.00E+00	0.00E+00	3.98E-01	2.95E-01	0.00E+00	6.93E-01
Climate change, short term								
	2017							
CRHT		9.84E-02	1.16E+03	1.10E+02	2.98E+03	4.78E+03	0.00E+00	9.03E+03
FFLT		5.58E-01	4.06E+01	1.90E+00	1.10E+03	-3.80E+03	0.00E+00	-2.66E+03
FFRAS		3.44E+03	9.83E+03	1.39E+00	3.88E+02	5.27E+03	0.00E+00	1.89E+04
MFHT		2.00E+03	7.72E+03	1.53E-01	2.36E+02	2.84E+03	7.27E+02	1.35E+04
MFLT		0.00E+00	1.10E+04	2.61E+00	5.64E+02	3.61E+03	0.00E+00	1.52E+04
MFOF		2.00E+03	7.72E+03	1.53E-01	4.02E+02	5.92E+03	7.27E+02	1.68E+04
MFRAS		2.76E+03	6.81E+03	7.94E-01	3.11E+02	3.75E+03	0.00E+00	1.36E+04
MOLT		0.00E+00	0.00E+00	0.00E+00	2.69E+02	7.26E+01	0.00E+00	3.42E+02
	2040							
CRHT		9.84E-02	9.72E+02	1.11E+02	2.98E+03	4.72E+03	0.00E+00	8.78E+03
FFLT		5.58E-01	4.06E+01	1.92E+00	1.10E+03	-3.80E+03	0.00E+00	-2.66E+03
FFRAS1		3.44E+03	6.64E+03	1.41E+00	3.88E+02	4.96E+03	0.00E+00	1.54E+04
FFRAS2		3.44E+03	7.79E+03	1.41E+00	3.88E+02	5.05E+03	0.00E+00	1.67E+04
MFHT1		2.00E+03	6.46E+03	1.55E-01	2.36E+02	2.56E+03	7.25E+02	1.20E+04
MFHT2		2.00E+03	7.56E+03	1.55E-01	2.36E+02	2.56E+03	7.25E+02	1.31E+04
MFLT1		0.00E+00	9.61E+03	2.64E+00	5.64E+02	3.43E+03	0.00E+00	1.36E+04
MFLT2		0.00E+00	9.83E+03	2.64E+00	5.64E+02	3.43E+03	0.00E+00	1.38E+04
MFOF1		2.00E+03	5.41E+03	1.55E-01	4.02E+02	5.04E+03	7.25E+02	1.36E+04
MFOF2		2.00E+03	6.33E+03	1.55E-01	4.02E+02	5.04E+03	7.25E+02	1.45E+04
MFRAS1		2.76E+03	4.53E+03	8.05E-01	3.11E+02	3.66E+03	0.00E+00	1.12E+04
MFRAS2		2.76E+03	5.29E+03	8.05E-01	3.11E+02	3.81E+03	0.00E+00	1.22E+04
MOLT		0.00E+00	0.00E+00	0.00E+00	2.69E+02	7.26E+01	0.00E+00	3.42E+02
Eutrophication								
	2017							
CRHT		2.39E-04	-1.80E+01	6.56E+01	7.23E+00	6.38E+00	0.00E+00	6.13E+01
FFLT		1.72E-03	5.33E-02	1.14E+00	1.69E+00	-8.54E+00	0.00E+00	-5.66E+00
FFRAS		8.26E+00	1.94E+01	8.34E-01	3.79E-01	8.93E+00	0.00E+00	3.78E+01
MFHT		4.75E+00	1.34E+01	9.16E-02	3.76E-01	7.36E+01	7.31E-01	9.29E+01
MFLT		0.00E+00	2.30E+01	1.56E+00	7.84E-01	1.97E+02	0.00E+00	2.23E+02
MFOF		4.75E+00	1.34E+01	9.16E-02	5.39E-01	8.11E+01	7.31E-01	1.01E+02
MFRAS		6.61E+00	1.18E+01	4.75E-01	3.03E-01	6.06E+00	0.00E+00	2.52E+01
MOLT		0.00E+00	0.00E+00	0.00E+00	2.97E-01	-5.58E+00	0.00E+00	-5.28E+00
	2040							
CRHT		2.39E-04	-1.50E+01	6.59E+01	7.23E+00	9.49E+00	0.00E+00	6.76E+01
FFLT		1.72E-03	5.33E-02	1.14E+00	1.69E+00	-8.52E+00	0.00E+00	-5.63E+00
FFRAS1		8.26E+00	1.33E+01	8.38E-01	3.79E-01	1.02E+01	0.00E+00	3.30E+01

<i>FFRAS2</i>		8.26E+00	1.78E+01	8.38E-01	3.79E-01	1.04E+01	0.00E+00	3.77E+01
<i>MFHT1</i>		4.75E+00	1.11E+01	9.20E-02	3.76E-01	6.05E+01	8.55E-01	7.77E+01
<i>MFHT2</i>		4.75E+00	2.24E+01	9.20E-02	3.76E-01	5.26E+01	8.55E-01	8.11E+01
<i>MFLT1</i>		0.00E+00	2.00E+01	1.57E+00	7.84E-01	1.69E+02	0.00E+00	1.91E+02
<i>MFLT2</i>		0.00E+00	2.07E+01	1.57E+00	7.84E-01	1.69E+02	0.00E+00	1.92E+02
<i>MFOF1</i>		4.75E+00	9.30E+00	9.20E-02	5.39E-01	5.04E+01	8.55E-01	6.59E+01
<i>MFOF2</i>		4.75E+00	1.87E+01	9.20E-02	5.39E-01	4.38E+01	8.55E-01	6.88E+01
<i>MFRAS1</i>		6.61E+00	7.78E+00	4.78E-01	3.03E-01	7.42E+00	0.00E+00	2.26E+01
<i>MFRAS2</i>		6.61E+00	1.57E+01	4.78E-01	3.03E-01	7.79E+00	0.00E+00	3.08E+01
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	2.97E-01	-5.58E+00	0.00E+00	-5.28E+00
Freshwater ecotoxicity								
2017								
<i>CRHT</i>		1.10E+03	4.36E+06	2.87E+06	2.64E+07	1.90E+08	0.00E+00	2.23E+08
<i>FFLT</i>		5.82E+03	1.43E+05	4.96E+04	5.00E+06	-1.96E+07	0.00E+00	-1.44E+07
<i>FFRAS</i>		3.81E+07	1.69E+07	3.64E+04	1.17E+06	1.24E+08	0.00E+00	1.80E+08
<i>MFHT</i>		2.27E+07	3.76E+07	4.00E+03	1.31E+06	8.47E+06	9.43E+06	7.96E+07
<i>MFLT</i>		0.00E+00	6.22E+07	6.82E+04	2.32E+06	1.19E+07	0.00E+00	7.65E+07
<i>MFOF</i>		2.27E+07	3.76E+07	4.00E+03	1.68E+06	1.53E+07	9.43E+06	8.67E+07
<i>MFRAS</i>		3.04E+07	3.32E+07	2.08E+04	9.37E+05	9.67E+07	0.00E+00	1.61E+08
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	1.09E+06	1.95E+05	0.00E+00	1.28E+06
2040								
<i>CRHT</i>		1.10E+03	3.65E+06	5.95E+06	2.64E+07	2.03E+08	0.00E+00	2.39E+08
<i>FFLT</i>		5.82E+03	1.43E+05	1.03E+05	5.00E+06	-1.94E+07	0.00E+00	-1.41E+07
<i>FFRAS1</i>		3.81E+07	1.28E+07	7.57E+04	1.17E+06	1.25E+08	0.00E+00	1.77E+08
<i>FFRAS2</i>		3.81E+07	2.13E+07	7.57E+04	1.17E+06	1.25E+08	0.00E+00	1.86E+08
<i>MFHT1</i>		2.27E+07	3.33E+07	8.31E+03	1.31E+06	7.62E+06	1.08E+07	7.57E+07
<i>MFHT2</i>		2.27E+07	9.27E+07	8.31E+03	1.31E+06	7.62E+06	1.08E+07	1.35E+08
<i>MFLT1</i>		0.00E+00	5.73E+07	1.42E+05	2.32E+06	1.13E+07	0.00E+00	7.11E+07
<i>MFLT2</i>		0.00E+00	5.78E+07	1.42E+05	2.32E+06	1.13E+07	0.00E+00	7.16E+07
<i>MFOF1</i>		2.27E+07	2.79E+07	8.31E+03	1.68E+06	1.30E+07	1.08E+07	7.60E+07
<i>MFOF2</i>		2.27E+07	7.76E+07	8.31E+03	1.68E+06	1.30E+07	1.08E+07	1.26E+08
<i>MFRAS1</i>		3.04E+07	2.33E+07	4.31E+04	9.37E+05	9.80E+07	0.00E+00	1.53E+08
<i>MFRAS2</i>		3.04E+07	6.49E+07	4.31E+04	9.37E+05	9.89E+07	0.00E+00	1.95E+08
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	1.09E+06	1.95E+05	0.00E+00	1.28E+06
Human toxicity cancer								
2017								
<i>CRHT</i>		6.08E-09	8.40E-05	1.23E-05	2.69E-04	1.11E-04	0.00E+00	4.76E-04
<i>FFLT</i>		3.89E-08	1.29E-06	2.13E-07	6.65E-05	-1.27E-04	0.00E+00	-5.86E-05
<i>FFRAS</i>		2.09E-04	7.95E-05	1.56E-07	2.81E-05	1.43E-04	0.00E+00	4.59E-04
<i>MFHT</i>		1.29E-04	1.57E-04	1.72E-08	1.99E-05	6.72E-05	1.69E-05	3.91E-04
<i>MFLT</i>		0.00E+00	2.58E-04	2.93E-07	2.83E-05	7.69E-05	0.00E+00	3.63E-04
<i>MFOF</i>		1.29E-04	1.57E-04	1.72E-08	3.02E-05	1.42E-04	1.69E-05	4.75E-04
<i>MFRAS</i>		1.67E-04	1.39E-04	8.91E-08	2.25E-05	9.80E-05	0.00E+00	4.27E-04
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	2.28E-05	1.88E-06	0.00E+00	2.47E-05
2040								
<i>CRHT</i>		6.08E-09	7.02E-05	1.57E-05	2.69E-04	1.41E-04	0.00E+00	4.96E-04
<i>FFLT</i>		3.89E-08	1.29E-06	2.72E-07	6.65E-05	-1.26E-04	0.00E+00	-5.83E-05
<i>FFRAS1</i>		2.09E-04	5.33E-05	2.00E-07	2.81E-05	1.52E-04	0.00E+00	4.42E-04
<i>FFRAS2</i>		2.09E-04	7.24E-05	2.00E-07	2.81E-05	1.55E-04	0.00E+00	4.64E-04
<i>MFHT1</i>		1.29E-04	1.34E-04	2.19E-08	1.99E-05	6.05E-05	1.80E-05	3.61E-04
<i>MFHT2</i>		1.29E-04	2.42E-04	2.19E-08	1.99E-05	6.05E-05	1.80E-05	4.69E-04
<i>MFLT1</i>		0.00E+00	2.28E-04	3.74E-07	2.83E-05	7.30E-05	0.00E+00	3.30E-04
<i>MFLT2</i>		0.00E+00	2.32E-04	3.74E-07	2.83E-05	7.30E-05	0.00E+00	3.34E-04
<i>MFOF1</i>		1.29E-04	1.12E-04	2.19E-08	3.02E-05	1.20E-04	1.80E-05	4.10E-04
<i>MFOF2</i>		1.29E-04	2.02E-04	2.19E-08	3.02E-05	1.20E-04	1.80E-05	5.00E-04
<i>MFRAS1</i>		1.67E-04	9.37E-05	1.14E-07	2.25E-05	1.11E-04	0.00E+00	3.94E-04
<i>MFRAS2</i>		1.67E-04	1.69E-04	1.14E-07	2.25E-05	1.16E-04	0.00E+00	4.75E-04
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	2.28E-05	1.88E-06	0.00E+00	2.47E-05
Human toxicity non cancer								
2017								
<i>CRHT</i>		1.87E-08	7.45E-05	3.48E-05	5.89E-04	-6.57E-04	0.00E+00	4.08E-05
<i>FFLT</i>		1.64E-07	4.88E-06	6.03E-07	1.75E-04	-1.00E-03	0.00E+00	-8.20E-04
<i>FFRAS</i>		6.14E-04	8.84E-04	4.43E-07	1.44E-05	2.21E-04	0.00E+00	1.73E-03
<i>MFHT</i>		3.58E-04	5.77E-04	4.86E-08	3.57E-05	1.77E-04	6.03E-05	1.21E-03
<i>MFLT</i>		0.00E+00	1.36E-03	8.29E-07	6.22E-05	1.99E-04	0.00E+00	1.62E-03
<i>MFOF</i>		3.58E-04	5.77E-04	4.86E-08	4.17E-05	3.44E-04	6.03E-05	1.38E-03
<i>MFRAS</i>		4.91E-04	5.09E-04	2.52E-07	1.15E-05	5.20E-05	0.00E+00	1.06E-03
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	1.75E-05	4.42E-06	0.00E+00	2.19E-05
2040								
<i>CRHT</i>		1.87E-08	6.23E-05	3.97E-05	5.89E-04	-4.48E-04	0.00E+00	2.42E-04

<i>FFLT</i>		1.64E-07	4.88E-06	6.88E-07	1.75E-04	-1.00E-03	0.00E+00	-8.20E-04
<i>FFRAS1</i>		6.14E-04	5.98E-04	5.05E-07	1.44E-05	3.29E-04	0.00E+00	1.56E-03
<i>FFRAS2</i>		6.14E-04	8.74E-04	5.05E-07	1.44E-05	3.53E-04	0.00E+00	1.86E-03
<i>MFHT1</i>		3.58E-04	4.89E-04	5.54E-08	3.57E-05	1.60E-04	6.13E-05	1.10E-03
<i>MFHT2</i>		3.58E-04	1.21E-03	5.54E-08	3.57E-05	1.60E-04	6.13E-05	1.83E-03
<i>MFLT1</i>		0.00E+00	1.20E-03	9.45E-07	6.22E-05	1.89E-04	0.00E+00	1.46E-03
<i>MFLT2</i>		0.00E+00	1.22E-03	9.45E-07	6.22E-05	1.89E-04	0.00E+00	1.47E-03
<i>MFOF1</i>		3.58E-04	4.09E-04	5.54E-08	4.17E-05	2.92E-04	6.13E-05	1.16E-03
<i>MFOF2</i>		3.58E-04	1.02E-03	5.54E-08	4.17E-05	2.92E-04	6.13E-05	1.77E-03
<i>MFRAS1</i>		4.91E-04	3.42E-04	2.88E-07	1.15E-05	1.79E-04	0.00E+00	1.02E-03
<i>MFRAS2</i>		4.91E-04	8.50E-04	2.88E-07	1.15E-05	2.21E-04	0.00E+00	1.57E-03
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	1.75E-05	4.42E-06	0.00E+00	2.19E-05
Land competition								
	2017							
<i>CRHT</i>		8.04E-03	2.69E+03	-1.80E+00	1.02E+03	4.69E+02	0.00E+00	4.17E+03
<i>FFLT</i>		2.08E-01	8.21E+00	-3.12E-02	1.95E+02	2.41E+01	0.00E+00	2.28E+02
<i>FFRAS</i>		2.81E+02	2.99E+03	-2.29E-02	1.99E+01	-2.58E+02	0.00E+00	3.03E+03
<i>MFHT</i>		1.61E+02	4.66E+02	-2.52E-03	3.98E+01	5.13E+02	-4.81E+01	1.13E+03
<i>MFLT</i>		0.00E+00	2.72E+03	-4.29E-02	2.53E+03	6.62E+02	0.00E+00	5.91E+03
<i>MFOF</i>		1.61E+02	4.66E+02	-2.52E-03	5.54E+01	1.09E+03	-4.81E+01	1.73E+03
<i>MFRAS</i>		2.24E+02	4.11E+02	-1.31E-02	1.59E+01	-2.45E+02	0.00E+00	4.07E+02
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	7.55E+02	3.54E+01	0.00E+00	7.90E+02
	2040							
<i>CRHT</i>		8.04E-03	2.25E+03	-1.59E+01	1.02E+03	3.80E+02	0.00E+00	3.63E+03
<i>FFLT</i>		2.08E-01	8.21E+00	-2.76E-01	1.95E+02	2.26E+01	0.00E+00	2.26E+02
<i>FFRAS1</i>		2.81E+02	2.03E+03	-2.03E-01	1.99E+01	-2.90E+02	0.00E+00	2.04E+03
<i>FFRAS2</i>		2.81E+02	3.26E+03	-2.03E-01	1.99E+01	-2.82E+02	0.00E+00	3.28E+03
<i>MFHT1</i>		1.61E+02	3.75E+02	-2.22E-02	3.98E+01	4.64E+02	-5.74E+01	9.81E+02
<i>MFHT2</i>		1.61E+02	2.60E+03	-2.22E-02	3.98E+01	4.64E+02	-5.74E+01	3.20E+03
<i>MFLT1</i>		0.00E+00	2.39E+03	-3.80E-01	2.53E+03	6.29E+02	0.00E+00	5.56E+03
<i>MFLT2</i>		0.00E+00	2.42E+03	-3.80E-01	2.53E+03	6.29E+02	0.00E+00	5.58E+03
<i>MFOF1</i>		1.61E+02	3.14E+02	-2.22E-02	5.54E+01	9.34E+02	-5.74E+01	1.41E+03
<i>MFOF2</i>		1.61E+02	2.17E+03	-2.22E-02	5.54E+01	9.34E+02	-5.74E+01	3.27E+03
<i>MFRAS1</i>		2.24E+02	2.62E+02	-1.16E-01	1.59E+01	-2.58E+02	0.00E+00	2.45E+02
<i>MFRAS2</i>		2.24E+02	1.82E+03	-1.16E-01	1.59E+01	-2.45E+02	0.00E+00	1.81E+03
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	7.55E+02	3.54E+01	0.00E+00	7.90E+02
Mineral resources use								
	2017							
<i>CRHT</i>		8.94E-04	2.12E+02	3.95E-01	8.78E+02	-7.27E+01	0.00E+00	1.02E+03
<i>FFLT</i>		1.19E-01	1.34E+00	6.85E-03	1.34E+02	-9.80E+01	0.00E+00	3.75E+01
<i>FFRAS</i>		2.44E+01	9.97E+01	5.02E-03	7.36E+01	1.79E+01	0.00E+00	2.16E+02
<i>MFHT</i>		1.50E+01	4.94E+01	5.51E-04	5.10E+01	2.34E+01	3.29E+01	1.72E+02
<i>MFLT</i>		0.00E+00	1.49E+02	9.41E-03	3.56E+01	2.27E+01	0.00E+00	2.07E+02
<i>MFOF</i>		1.50E+01	4.94E+01	5.51E-04	5.17E+01	3.86E+01	3.29E+01	1.88E+02
<i>MFRAS</i>		1.96E+01	4.35E+01	2.86E-03	5.88E+01	2.08E+00	0.00E+00	1.24E+02
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	6.18E+01	4.69E-01	0.00E+00	6.23E+01
	2040							
<i>CRHT</i>		8.94E-04	1.77E+02	3.01E-01	8.78E+02	-5.47E+01	0.00E+00	1.00E+03
<i>FFLT</i>		1.19E-01	1.34E+00	5.21E-03	1.34E+02	-9.81E+01	0.00E+00	3.75E+01
<i>FFRAS1</i>		2.44E+01	6.78E+01	3.82E-03	7.36E+01	2.72E+01	0.00E+00	1.93E+02
<i>FFRAS2</i>		2.44E+01	1.13E+02	3.82E-03	7.36E+01	2.96E+01	0.00E+00	2.41E+02
<i>MFHT1</i>		1.50E+01	4.15E+01	4.19E-04	5.10E+01	2.11E+01	3.28E+01	1.61E+02
<i>MFHT2</i>		1.50E+01	1.48E+02	4.19E-04	5.10E+01	2.11E+01	3.28E+01	2.68E+02
<i>MFLT1</i>		0.00E+00	1.32E+02	7.16E-03	3.56E+01	2.15E+01	0.00E+00	1.89E+02
<i>MFLT2</i>		0.00E+00	1.33E+02	7.16E-03	3.56E+01	2.15E+01	0.00E+00	1.91E+02
<i>MFOF1</i>		1.50E+01	3.48E+01	4.19E-04	5.17E+01	3.28E+01	3.28E+01	1.67E+02
<i>MFOF2</i>		1.50E+01	1.24E+02	4.19E-04	5.17E+01	3.28E+01	3.28E+01	2.56E+02
<i>MFRAS1</i>		1.96E+01	2.91E+01	2.18E-03	5.88E+01	1.35E+01	0.00E+00	1.21E+02
<i>MFRAS2</i>		1.96E+01	1.04E+02	2.18E-03	5.88E+01	1.76E+01	0.00E+00	2.00E+02
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	6.18E+01	4.69E-01	0.00E+00	6.23E+01
NPPU								
	2017							
<i>CRHT</i>		0.00E+00	9.91E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.91E+03
<i>FFLT</i>		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
<i>FFRAS</i>		0.00E+00	1.02E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+04
<i>MFHT</i>		0.00E+00	6.13E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	4.70E+04
<i>MFLT</i>		0.00E+00	1.01E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+05
<i>MFOF</i>		0.00E+00	6.13E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	4.70E+04
<i>MFRAS</i>		0.00E+00	5.41E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.41E+04
<i>MOLT</i>		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

<i>CRHT</i> <i>FFLT</i> <i>FFRAS1</i> <i>FFRAS2</i> <i>MFHT1</i> <i>MFHT2</i> <i>MFLT1</i> <i>MFLT2</i> <i>MFOF1</i> <i>MFOF2</i> <i>MFRAS1</i> <i>MFRAS2</i> <i>MOLT</i> <i>Water scarcity</i>	2040	0.00E+00	8.29E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.29E+03
		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		0.00E+00	3.02E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.02E+03
		0.00E+00	1.18E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.18E+03
		0.00E+00	1.91E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	4.75E+03	
		0.00E+00	2.44E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	1.01E+04	
		0.00E+00	3.28E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.28E+04	
		0.00E+00	8.06E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.06E+04	
		0.00E+00	1.60E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	1.65E+03	
		0.00E+00	2.04E+04	0.00E+00	0.00E+00	0.00E+00	-1.43E+04	6.12E+03	
		0.00E+00	1.34E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.34E+04	
		0.00E+00	1.71E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E+04	
		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
<i>CRHT</i> <i>FFLT</i> <i>FFRAS</i> <i>MFHT</i> <i>MFLT</i> <i>MFOF</i> <i>MFRAS</i> <i>MOLT</i>	2017	1.08E-02	6.69E+02	8.19E-02	6.97E+02	-5.26E+02	0.00E+00	8.40E+02	
		2.43E-01	6.13E+00	1.42E-03	3.13E+02	-1.38E+03	0.00E+00	-1.06E+03	
		3.95E+03	4.54E+03	1.04E-03	2.48E+02	6.37E+02	0.00E+00	9.37E+03	
		2.32E+03	6.16E+02	1.14E-04	8.72E+01	9.34E+02	1.05E+02	4.06E+03	
		0.00E+00	5.26E+03	1.95E-03	1.85E+02	5.48E+02	0.00E+00	5.99E+03	
		2.32E+03	6.16E+02	1.14E-04	1.40E+02	1.15E+03	1.05E+02	4.33E+03	
		3.16E+03	5.43E+02	5.93E-04	1.98E+02	3.27E+02	0.00E+00	4.23E+03	
		0.00E+00	0.00E+00	0.00E+00	1.80E+02	1.68E+01	0.00E+00	1.97E+02	
	<i>CRHT</i> <i>FFLT</i> <i>FFRAS1</i> <i>FFRAS2</i> <i>MFHT1</i> <i>MFHT2</i> <i>MFLT1</i> <i>MFLT2</i> <i>MFOF1</i> <i>MFOF2</i> <i>MFRAS1</i> <i>MFRAS2</i> <i>MOLT</i> <i>Fossil and nuclear energy use</i>	2040	1.08E-02	5.59E+02	-1.22E+00	6.97E+02	-3.01E+02	0.00E+00	9.54E+02
			2.43E-01	6.13E+00	-2.11E-02	3.13E+02	-1.38E+03	0.00E+00	-1.06E+03
			3.95E+03	3.10E+03	-1.55E-02	2.48E+02	7.13E+02	0.00E+00	8.01E+03
			3.95E+03	5.10E+03	-1.55E-02	2.48E+02	7.50E+02	0.00E+00	1.00E+04
			2.32E+03	5.13E+02	-1.70E-03	8.72E+01	8.40E+02	1.06E+02	3.87E+03
			2.32E+03	5.36E+03	-1.70E-03	8.72E+01	8.40E+02	1.06E+02	8.71E+03
		0.00E+00	4.69E+03	-2.90E-02	1.85E+02	5.21E+02	0.00E+00	5.40E+03	
		0.00E+00	4.71E+03	-2.90E-02	1.85E+02	5.21E+02	0.00E+00	5.42E+03	
		2.32E+03	4.29E+02	-1.70E-03	1.40E+02	9.79E+02	1.06E+02	3.97E+03	
		2.32E+03	4.48E+03	-1.70E-03	1.40E+02	9.79E+02	1.06E+02	8.03E+03	
		3.16E+03	3.59E+02	-8.82E-03	1.98E+02	4.47E+02	0.00E+00	4.16E+03	
		3.16E+03	3.75E+03	-8.82E-03	1.98E+02	5.12E+02	0.00E+00	7.62E+03	
		0.00E+00	0.00E+00	0.00E+00	1.80E+02	1.68E+01	0.00E+00	1.97E+02	
<i>CRHT</i> <i>FFLT</i> <i>FFRAS</i> <i>MFHT</i> <i>MFLT</i> <i>MFOF</i> <i>MFRAS</i> <i>MOLT</i>	2017	1.48E+00	2.15E+04	1.31E+03	3.26E+04	1.72E+05	0.00E+00	2.27E+05	
		7.45E+00	6.50E+02	2.27E+01	1.01E+04	-2.31E+04	0.00E+00	-1.23E+04	
		5.18E+04	3.07E+04	1.67E+01	5.40E+03	1.16E+05	0.00E+00	2.04E+05	
		3.02E+04	4.01E+04	1.83E+00	3.34E+03	5.41E+04	1.02E+04	1.38E+05	
		0.00E+00	8.39E+04	3.12E+01	9.30E+03	6.15E+04	0.00E+00	1.55E+05	
		3.02E+04	4.01E+04	1.83E+00	7.32E+03	1.00E+05	1.02E+04	1.88E+05	
		4.15E+04	3.54E+04	9.50E+00	4.32E+03	8.95E+04	0.00E+00	1.71E+05	
		0.00E+00	0.00E+00	0.00E+00	5.04E+03	1.30E+03	0.00E+00	6.33E+03	
	<i>CRHT</i> <i>FFLT</i> <i>FFRAS1</i> <i>FFRAS2</i> <i>MFHT1</i> <i>MFHT2</i> <i>MFLT1</i> <i>MFLT2</i> <i>MFOF1</i> <i>MFOF2</i> <i>MFRAS1</i> <i>MFRAS2</i> <i>MOLT</i>	2040	1.48E+00	1.80E+04	1.16E+03	3.26E+04	1.55E+05	0.00E+00	2.07E+05
			7.45E+00	6.50E+02	2.00E+01	1.01E+04	-2.31E+04	0.00E+00	-1.23E+04
			5.18E+04	2.05E+04	1.47E+01	5.40E+03	1.00E+05	0.00E+00	1.78E+05
			5.18E+04	2.85E+04	1.47E+01	5.40E+03	1.01E+05	0.00E+00	1.87E+05
			3.02E+04	3.21E+04	1.61E+00	3.34E+03	4.87E+04	1.01E+04	1.24E+05
			3.02E+04	5.58E+04	1.61E+00	3.34E+03	4.87E+04	1.01E+04	1.48E+05
		0.00E+00	7.13E+04	2.75E+01	9.30E+03	5.85E+04	0.00E+00	1.39E+05	
		0.00E+00	7.46E+04	2.75E+01	9.30E+03	5.85E+04	0.00E+00	1.42E+05	
		3.02E+04	2.69E+04	1.61E+00	7.32E+03	8.50E+04	1.01E+04	1.60E+05	
		3.02E+04	4.67E+04	1.61E+00	7.32E+03	8.50E+04	1.01E+04	1.79E+05	
		4.15E+04	2.25E+04	8.38E+00	4.32E+03	7.81E+04	0.00E+00	1.46E+05	
		4.15E+04	3.91E+04	8.38E+00	4.32E+03	7.92E+04	0.00E+00	1.64E+05	
		0.00E+00	0.00E+00	0.00E+00	5.04E+03	1.30E+03	0.00E+00	6.33E+03	

Table S4: Quantified sensitivity analysis.

	FCR-	FCR+	Insect-	Insect+	Boats-	Boats+	Elec-	Elec+
CRHT								
Acidification								
2017	- 0.04	0.04	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.03	0.03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Climate change, short term								
2017	- 0.13	0.13	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.11	0.11	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Eutrophication								
2017	0.29	- 0.29	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	0.22	- 0.22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fossil and nuclear energy use								
2017	- 0.09	0.09	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.09	0.09	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Freshwater ecotoxicity								
2017	- 0.02	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.02	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity cancer								
2017	- 0.18	0.18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.14	0.14	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity non cancer								
2017	- 1.83	1.83	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.26	0.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Land competition								
2017	- 0.64	0.64	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.62	0.62	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mineral resources use								
2017	- 0.21	0.21	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.18	0.18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NPPU								
2017	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water scarcity								
2017	- 0.80	0.80	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.59	0.59	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
FFRAS1								
Acidification								
2017	- 0.31	0.31	n.a.	n.a.	n.a.	n.a.	- 0.52	0.52
2040	- 0.23	0.23	n.a.	n.a.	n.a.	n.a.	- 0.56	0.56
Climate change, short term								
2017	- 0.52	0.52	n.a.	n.a.	n.a.	n.a.	- 0.34	0.34
2040	- 0.43	0.43	n.a.	n.a.	n.a.	n.a.	- 0.35	0.35
Eutrophication								
2017	- 0.51	0.51	n.a.	n.a.	n.a.	n.a.	- 0.30	0.30
2040	- 0.40	0.40	n.a.	n.a.	n.a.	n.a.	- 0.34	0.34
Fossil and nuclear energy use								
2017	- 0.15	0.15	n.a.	n.a.	n.a.	n.a.	- 0.60	0.60
2040	- 0.12	0.12	n.a.	n.a.	n.a.	n.a.	- 0.58	0.58
Freshwater ecotoxicity								
2017	- 0.09	0.09	n.a.	n.a.	n.a.	n.a.	- 0.72	0.72
2040	- 0.07	0.07	n.a.	n.a.	n.a.	n.a.	- 0.72	0.72
Human toxicity cancer								
2017	- 0.17	0.17	n.a.	n.a.	n.a.	n.a.	- 0.39	0.39
2040	- 0.12	0.12	n.a.	n.a.	n.a.	n.a.	- 0.37	0.37
Human toxicity non cancer								
2017	- 0.51	0.51	n.a.	n.a.	n.a.	n.a.	- 0.30	0.30
2040	- 0.38	0.38	n.a.	n.a.	n.a.	n.a.	- 0.29	0.29
Land competition								
2017	- 0.99	0.99	n.a.	n.a.	n.a.	n.a.	0.07	- 0.07
2040	- 0.99	0.99	n.a.	n.a.	n.a.	n.a.	0.14	- 0.14
Mineral resources use								
2017	- 0.46	0.46	n.a.	n.a.	n.a.	n.a.	- 0.21	0.21
2040	- 0.35	0.35	n.a.	n.a.	n.a.	n.a.	- 0.19	0.19

NPPU									
2017	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	-	-	
2040	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	-	-	
Water scarcity									
2017	- 0.48	0.48	n.a.	n.a.	n.a.	n.a.	- 0.05	0.05	
2040	- 0.39	0.39	n.a.	n.a.	n.a.	n.a.	- 0.05	0.05	
FFRAS2									
Acidification									
2017	- 0.31	0.31	-	-	n.a.	n.a.	- 0.52	0.52	
2040	- 0.28	0.28	- 0.06	0.06	n.a.	n.a.	- 0.51	0.51	
Climate change, short term									
2017	- 0.52	0.52	-	-	n.a.	n.a.	- 0.34	0.34	
2040	- 0.47	0.47	- 0.06	0.06	n.a.	n.a.	- 0.33	0.33	
Eutrophication									
2017	- 0.51	0.51	-	-	n.a.	n.a.	- 0.30	0.30	
2040	- 0.47	0.47	- 0.11	0.11	n.a.	n.a.	- 0.30	0.30	
Fossil and nuclear energy use									
2017	- 0.15	0.15	-	-	n.a.	n.a.	- 0.60	0.60	
2040	- 0.15	0.15	- 0.03	0.03	n.a.	n.a.	- 0.55	0.55	
Freshwater ecotoxicity									
2017	- 0.09	0.09	-	-	n.a.	n.a.	- 0.72	0.72	
2040	- 0.11	0.11	- 0.01	0.01	n.a.	n.a.	- 0.69	0.69	
Human toxicity cancer									
2017	- 0.17	0.17	-	-	n.a.	n.a.	- 0.39	0.39	
2040	- 0.16	0.16	- 0.01	0.01	n.a.	n.a.	- 0.35	0.35	
Human toxicity non cancer									
2017	- 0.51	0.51	-	-	n.a.	n.a.	- 0.30	0.30	
2040	- 0.47	0.47	- 0.14	0.14	n.a.	n.a.	- 0.25	0.25	
Land competition									
2017	- 0.99	0.99	-	-	n.a.	n.a.	0.07	- 0.07	
2040	- 0.99	0.99	- 0.37	0.37	n.a.	n.a.	0.09	- 0.09	
Mineral resources use									
2017	- 0.46	0.46	-	-	n.a.	n.a.	- 0.21	0.21	
2040	- 0.47	0.47	- 0.12	0.12	n.a.	n.a.	- 0.16	0.16	
NPPU									
2017	- 1.00	1.00	-	-	n.a.	n.a.	-	-	
2040	- 1.00	1.00	- 0.30	0.30	n.a.	n.a.	-	-	
Water scarcity									
2017	- 0.48	0.48	-	-	n.a.	n.a.	- 0.05	0.05	
2040	- 0.51	0.51	- 0.19	0.19	n.a.	n.a.	- 0.04	0.04	
MFHT1									
Acidification									
2017	- 0.53	0.53	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.47	0.47	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Climate change, short term									
2017	- 0.57	0.57	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.54	0.54	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Eutrophication									
2017	- 0.89	0.89	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.87	0.87	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Fossil and nuclear energy use									
2017	- 0.29	0.29	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.26	0.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Freshwater ecotoxicity									
2017	- 0.47	0.47	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.44	0.44	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Human toxicity cancer									
2017	- 0.40	0.40	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.37	0.37	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Human toxicity non cancer									
2017	- 0.48	0.48	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.44	0.44	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Land competition									
2017	- 0.41	0.41	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
2040	- 0.38	0.38	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Mineral resources use									

	2017	- 0.29	0.29	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.26	0.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NPPU									
	2017	- 1.30	1.30	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 4.01	4.01	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water scarcity									
	2017	- 0.15	0.15	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.13	0.13	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MFHT2									
Acidification									
	2017	- 0.53	0.53	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.64	0.64	- 0.10	0.10	n.a.	n.a.	n.a.	n.a.
Climate change, short term									
	2017	- 0.57	0.57	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.58	0.58	- 0.13	0.13	n.a.	n.a.	n.a.	n.a.
Eutrophication									
	2017	- 0.89	0.89	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.87	0.87	- 0.09	0.09	n.a.	n.a.	n.a.	n.a.
Fossil and nuclear energy use									
	2017	- 0.29	0.29	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.38	0.38	- 0.07	0.07	n.a.	n.a.	n.a.	n.a.
Freshwater ecotoxicity									
	2017	- 0.47	0.47	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.69	0.69	- 0.02	0.02	n.a.	n.a.	n.a.	n.a.
Human toxicity cancer									
	2017	- 0.40	0.40	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.51	0.51	- 0.02	0.02	n.a.	n.a.	n.a.	n.a.
Human toxicity non cancer									
	2017	- 0.48	0.48	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.66	0.66	- 0.26	0.26	n.a.	n.a.	n.a.	n.a.
Land competition									
	2017	- 0.41	0.41	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.81	0.81	- 0.69	0.69	n.a.	n.a.	n.a.	n.a.
Mineral resources use									
	2017	- 0.29	0.29	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.55	0.55	- 0.21	0.21	n.a.	n.a.	n.a.	n.a.
NPPU									
	2017	- 1.30	1.30	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 2.42	2.42	- 0.06	0.06	n.a.	n.a.	n.a.	n.a.
Water scarcity									
	2017	- 0.15	0.15	-	-	n.a.	n.a.	n.a.	n.a.
	2040	- 0.61	0.61	- 0.41	0.41	n.a.	n.a.	n.a.	n.a.
MFLT1									
Acidification									
	2017	- 0.75	0.75	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.71	0.71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Climate change, short term									
	2017	- 0.73	0.73	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.71	0.71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Eutrophication									
	2017	- 0.97	0.97	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.96	0.96	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fossil and nuclear energy use									
	2017	- 0.54	0.54	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.51	0.51	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Freshwater ecotoxicity									
	2017	- 0.81	0.81	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.81	0.81	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity cancer									
	2017	- 0.71	0.71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.69	0.69	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity non cancer									
	2017	- 0.84	0.84	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2040	- 0.83	0.83	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Land competition									
	2017	- 0.46	0.46	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

2040	- 0.43	0.43	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mineral resources use								
2017	- 0.72	0.72	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.70	0.70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NPPU								
2017	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water scarcity								
2017	- 0.88	0.88	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.87	0.87	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MFLT2								
Acidification								
2017	- 0.75	0.75	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.74	0.74	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Climate change, short term								
2017	- 0.73	0.73	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.71	0.71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Eutrophication								
2017	- 0.97	0.97	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.96	0.96	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fossil and nuclear energy use								
2017	- 0.54	0.54	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.52	0.52	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Freshwater ecotoxicity								
2017	- 0.81	0.81	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.81	0.81	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity cancer								
2017	- 0.71	0.71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.70	0.70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Human toxicity non cancer								
2017	- 0.84	0.84	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.83	0.83	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Land competition								
2017	- 0.46	0.46	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.43	0.43	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mineral resources use								
2017	- 0.72	0.72	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.70	0.70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NPPU								
2017	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water scarcity								
2017	- 0.88	0.88	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2040	- 0.87	0.87	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MFOF1								
Acidification								
2017	- 0.43	0.43	n.a.	n.a.	- 0.22	0.22	n.a.	n.a.
2040	- 0.35	0.35	n.a.	n.a.	- 0.24	0.24	n.a.	n.a.
Climate change, short term								
2017	- 0.46	0.46	n.a.	n.a.	- 0.23	0.23	n.a.	n.a.
2040	- 0.40	0.40	n.a.	n.a.	- 0.24	0.24	n.a.	n.a.
Eutrophication								
2017	- 0.86	0.86	n.a.	n.a.	- 0.04	0.04	n.a.	n.a.
2040	- 0.80	0.80	n.a.	n.a.	- 0.06	0.06	n.a.	n.a.
Fossil and nuclear energy use								
2017	- 0.21	0.21	n.a.	n.a.	- 0.32	0.32	n.a.	n.a.
2040	- 0.17	0.17	n.a.	n.a.	- 0.32	0.32	n.a.	n.a.
Freshwater ecotoxicity								
2017	- 0.43	0.43	n.a.	n.a.	- 0.10	0.10	n.a.	n.a.
2040	- 0.37	0.37	n.a.	n.a.	- 0.10	0.10	n.a.	n.a.
Human toxicity cancer								
2017	- 0.33	0.33	n.a.	n.a.	- 0.20	0.20	n.a.	n.a.
2040	- 0.27	0.27	n.a.	n.a.	- 0.20	0.20	n.a.	n.a.
Human toxicity non cancer								
2017	- 0.42	0.42	n.a.	n.a.	- 0.16	0.16	n.a.	n.a.
2040	- 0.35	0.35	n.a.	n.a.	- 0.16	0.16	n.a.	n.a.

Land competition									
2017	- 0.27	0.27	n.a.	n.a.	- 0.44	0.44	n.a.	n.a.	
2040	- 0.22	0.22	n.a.	n.a.	- 0.46	0.46	n.a.	n.a.	
Mineral resources use									
2017	- 0.26	0.26	n.a.	n.a.	- 0.10	0.10	n.a.	n.a.	
2040	- 0.21	0.21	n.a.	n.a.	- 0.10	0.10	n.a.	n.a.	
NPPU									
2017	- 1.30	1.30	n.a.	n.a.	-	-	n.a.	n.a.	
2040	- 9.68	9.68	n.a.	n.a.	-	-	n.a.	n.a.	
Water scarcity									
2017	- 0.14	0.14	n.a.	n.a.	- 0.06	0.06	n.a.	n.a.	
2040	- 0.11	0.11	n.a.	n.a.	- 0.06	0.06	n.a.	n.a.	
MFOF2									
Acidification									
2017	- 0.43	0.43	-	-	- 0.22	0.22	n.a.	n.a.	
2040	- 0.51	0.51	- 0.08	0.08	- 0.18	0.18	n.a.	n.a.	
Climate change, short term									
2017	- 0.46	0.46	-	-	- 0.23	0.23	n.a.	n.a.	
2040	- 0.44	0.44	- 0.10	0.10	- 0.23	0.23	n.a.	n.a.	
Eutrophication									
2017	- 0.86	0.86	-	-	- 0.04	0.04	n.a.	n.a.	
2040	- 0.81	0.81	- 0.09	0.09	- 0.05	0.05	n.a.	n.a.	
Fossil and nuclear energy use									
2017	- 0.21	0.21	-	-	- 0.32	0.32	n.a.	n.a.	
2040	- 0.26	0.26	- 0.05	0.05	- 0.28	0.28	n.a.	n.a.	
Freshwater ecotoxicity									
2017	- 0.43	0.43	-	-	- 0.10	0.10	n.a.	n.a.	
2040	- 0.62	0.62	- 0.02	0.02	- 0.06	0.06	n.a.	n.a.	
Human toxicity cancer									
2017	- 0.33	0.33	-	-	- 0.20	0.20	n.a.	n.a.	
2040	- 0.40	0.40	- 0.02	0.02	- 0.16	0.16	n.a.	n.a.	
Human toxicity non cancer									
2017	- 0.42	0.42	-	-	- 0.16	0.16	n.a.	n.a.	
2040	- 0.57	0.57	- 0.22	0.22	- 0.10	0.10	n.a.	n.a.	
Land competition									
2017	- 0.27	0.27	-	-	- 0.44	0.44	n.a.	n.a.	
2040	- 0.67	0.67	- 0.57	0.57	- 0.20	0.20	n.a.	n.a.	
Mineral resources use									
2017	- 0.26	0.26	-	-	- 0.10	0.10	n.a.	n.a.	
2040	- 0.48	0.48	- 0.18	0.18	- 0.07	0.07	n.a.	n.a.	
NPPU									
2017	- 1.30	1.30	-	-	-	-	n.a.	n.a.	
2040	- 3.34	3.34	- 0.09	0.09	-	-	n.a.	n.a.	
Water scarcity									
2017	- 0.14	0.14	-	-	- 0.06	0.06	n.a.	n.a.	
2040	- 0.56	0.56	- 0.37	0.37	- 0.03	0.03	n.a.	n.a.	
MFRAS1									
Acidification									
2017	- 0.44	0.44	n.a.	n.a.	n.a.	n.a.	- 0.45	0.45	
2040	- 0.31	0.31	n.a.	n.a.	n.a.	n.a.	- 0.51	0.51	
Climate change, short term									
2017	- 0.50	0.50	n.a.	n.a.	n.a.	n.a.	- 0.38	0.38	
2040	- 0.40	0.40	n.a.	n.a.	n.a.	n.a.	- 0.39	0.39	
Eutrophication									
2017	- 0.47	0.47	n.a.	n.a.	n.a.	n.a.	- 0.36	0.36	
2040	- 0.34	0.34	n.a.	n.a.	n.a.	n.a.	- 0.40	0.40	
Fossil and nuclear energy use									
2017	- 0.21	0.21	n.a.	n.a.	n.a.	n.a.	- 0.58	0.58	
2040	- 0.15	0.15	n.a.	n.a.	n.a.	n.a.	- 0.56	0.56	
Freshwater ecotoxicity									
2017	- 0.21	0.21	n.a.	n.a.	n.a.	n.a.	- 0.65	0.65	
2040	- 0.15	0.15	n.a.	n.a.	n.a.	n.a.	- 0.67	0.67	
Human toxicity cancer									
2017	- 0.33	0.33	n.a.	n.a.	n.a.	n.a.	- 0.33	0.33	
2040	- 0.24	0.24	n.a.	n.a.	n.a.	n.a.	- 0.33	0.33	
Human toxicity non cancer									

	2017	- 0.48	0.48	n.a.	n.a.	n.a.	n.a.	- 0.39	0.39
	2040	- 0.33	0.33	n.a.	n.a.	n.a.	n.a.	- 0.36	0.36
Land competition									
	2017	- 1.01	1.01	n.a.	n.a.	n.a.	n.a.	0.39	- 0.39
	2040	- 1.07	1.07	n.a.	n.a.	n.a.	n.a.	0.92	- 0.92
Mineral resources use									
	2017	- 0.35	0.35	n.a.	n.a.	n.a.	n.a.	- 0.29	0.29
	2040	- 0.24	0.24	n.a.	n.a.	n.a.	n.a.	- 0.25	0.25
NPPU									
	2017	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	-	-
	2040	- 1.00	1.00	n.a.	n.a.	n.a.	n.a.	-	-
Water scarcity									
	2017	- 0.13	0.13	n.a.	n.a.	n.a.	n.a.	- 0.09	0.09
	2040	- 0.09	0.09	n.a.	n.a.	n.a.	n.a.	- 0.08	0.08
MFRAS2									
Acidification									
	2017	- 0.44	0.44	-	-	n.a.	n.a.	- 0.45	0.45
	2040	- 0.46	0.46	- 0.07	0.07	n.a.	n.a.	- 0.39	0.39
Climate change, short term									
	2017	- 0.50	0.50	-	-	n.a.	n.a.	- 0.38	0.38
	2040	- 0.44	0.44	- 0.10	0.10	n.a.	n.a.	- 0.36	0.36
Eutrophication									
	2017	- 0.47	0.47	-	-	n.a.	n.a.	- 0.36	0.36
	2040	- 0.51	0.51	- 0.17	0.17	n.a.	n.a.	- 0.29	0.29
Fossil and nuclear energy use									
	2017	- 0.21	0.21	-	-	n.a.	n.a.	- 0.58	0.58
	2040	- 0.24	0.24	- 0.04	0.04	n.a.	n.a.	- 0.50	0.50
Freshwater ecotoxicity									
	2017	- 0.21	0.21	-	-	n.a.	n.a.	- 0.65	0.65
	2040	- 0.33	0.33	- 0.01	0.01	n.a.	n.a.	- 0.52	0.52
Human toxicity cancer									
	2017	- 0.33	0.33	-	-	n.a.	n.a.	- 0.33	0.33
	2040	- 0.36	0.36	- 0.01	0.01	n.a.	n.a.	- 0.28	0.28
Human toxicity non cancer									
	2017	- 0.48	0.48	-	-	n.a.	n.a.	- 0.39	0.39
	2040	- 0.54	0.54	- 0.21	0.21	n.a.	n.a.	- 0.23	0.23
Land competition									
	2017	- 1.01	1.01	-	-	n.a.	n.a.	0.39	- 0.39
	2040	- 1.00	1.00	- 0.86	0.86	n.a.	n.a.	0.12	- 0.12
Mineral resources use									
	2017	- 0.35	0.35	-	-	n.a.	n.a.	- 0.29	0.29
	2040	- 0.52	0.52	- 0.19	0.19	n.a.	n.a.	- 0.15	0.15
NPPU									
	2017	- 1.00	1.00	-	-	n.a.	n.a.	-	-
	2040	- 1.00	1.00	- 0.03	0.03	n.a.	n.a.	-	-
Water scarcity									
	2017	- 0.13	0.13	-	-	n.a.	n.a.	- 0.09	0.09
	2040	- 0.49	0.49	- 0.33	0.33	n.a.	n.a.	- 0.04	0.04

Table S5: Characterized results used ReCiPe 2016 Midpoint.

	2017	2040
<i>Fine particulate matter formation</i> (kg PM2.5 equivalent)		
CRHT	1.17E+01	1.22E+01
FFLT	-2.00E+00	-1.99E+00
FFRAS1	1.61E+01	1.47E+01
FFRAS2	1.61E+01	1.52E+01
MFHT1	2.09E+01	1.79E+01
MFHT2	2.09E+01	2.10E+01
MFLT1	2.58E+01	2.18E+01
MFLT2	2.58E+01	2.34E+01
MFOF1	2.41E+01	1.92E+01
MFOF2	2.41E+01	2.18E+01
MFRAS1	1.95E+01	1.65E+01
MFRAS2	1.95E+01	1.86E+01
MOLT	4.52E-01	4.52E-01
<i>Fossil resource scarcity</i> (kg oil equivalent)		
CRHT	4.74E+03	4.28E+03
FFLT	-2.54E+02	-2.54E+02
FFRAS1	4.30E+03	3.76E+03
FFRAS2	4.30E+03	3.91E+03
MFHT1	2.92E+03	2.62E+03
MFHT2	2.92E+03	3.02E+03
MFLT1	3.40E+03	3.05E+03
MFLT2	3.40E+03	3.12E+03
MFOF1	4.01E+03	3.38E+03
MFOF2	4.01E+03	3.72E+03
MFRAS1	3.49E+03	2.98E+03
MFRAS2	3.49E+03	3.27E+03
MOLT	1.30E+02	1.30E+02
<i>Freshwater ecotoxicity</i> (kg 1.4-DCB)		
CRHT	6.13E+02	6.09E+02
FFLT	-1.67E+02	-1.66E+02
FFRAS1	5.57E+02	5.09E+02
FFRAS2	5.57E+02	5.40E+02
MFHT1	2.16E+02	2.06E+02
MFHT2	2.16E+02	3.85E+02
MFLT1	1.82E+02	1.68E+02
MFLT2	1.82E+02	1.69E+02
MFOF1	2.26E+02	2.01E+02
MFOF2	2.26E+02	3.52E+02

<i>MFRAS1</i>	4.90E+02	4.72E+02
<i>MFRAS2</i>	4.90E+02	5.98E+02
<i>MOLT</i>	3.85E+00	3.85E+00
<i>Freshwater eutrophication</i> (kg P equivalent)		
<i>CRHT</i>	3.64E+00	3.92E+00
<i>FFLT</i>	-1.11E+00	-1.11E+00
<i>FFRAS1</i>	4.37E+00	4.03E+00
<i>FFRAS2</i>	4.37E+00	4.35E+00
<i>MFHT1</i>	3.91E+00	3.61E+00
<i>MFHT2</i>	3.91E+00	4.69E+00
<i>MFLT1</i>	3.75E+00	3.42E+00
<i>MFLT2</i>	3.75E+00	3.46E+00
<i>MFOF1</i>	4.81E+00	4.11E+00
<i>MFOF2</i>	4.81E+00	5.01E+00
<i>MFRAS1</i>	4.05E+00	3.86E+00
<i>MFRAS2</i>	4.05E+00	4.62E+00
<i>MOLT</i>	8.56E-02	8.56E-02
<i>Global warming</i> (kg CO2 equivalent)		
<i>CRHT</i>	9.26E+03	8.61E+03
<i>FFLT</i>	-2.66E+03	-2.66E+03
<i>FFRAS1</i>	1.92E+04	1.58E+04
<i>FFRAS2</i>	1.92E+04	1.69E+04
<i>MFHT1</i>	1.35E+04	1.20E+04
<i>MFHT2</i>	1.35E+04	1.31E+04
<i>MFLT1</i>	1.52E+04	1.36E+04
<i>MFLT2</i>	1.52E+04	1.38E+04
<i>MFOF1</i>	1.68E+04	1.36E+04
<i>MFOF2</i>	1.68E+04	1.45E+04
<i>MFRAS1</i>	1.36E+04	1.14E+04
<i>MFRAS2</i>	1.36E+04	1.22E+04
<i>MOLT</i>	3.42E+02	3.42E+02
<i>Human carcinogenic toxicity</i> (kg 1.4-DCB)		
<i>CRHT</i>	3.76E+02	3.79E+02
<i>FFLT</i>	-3.89E+01	-3.87E+01
<i>FFRAS1</i>	2.88E+02	2.73E+02
<i>FFRAS2</i>	2.88E+02	2.90E+02
<i>MFHT1</i>	2.59E+02	2.41E+02
<i>MFHT2</i>	2.59E+02	3.28E+02
<i>MFLT1</i>	2.30E+02	2.09E+02
<i>MFLT2</i>	2.30E+02	2.12E+02
<i>MFOF1</i>	3.18E+02	2.76E+02
<i>MFOF2</i>	3.18E+02	3.49E+02

<i>MFRAS1</i>	2.98E+02	2.82E+02
<i>MFRAS2</i>	2.98E+02	3.43E+02
<i>MOLT</i>	1.85E+01	1.85E+01
<i>Human non-carcinogenic toxicity</i> <i>(kg 1.4-DCB)</i>		
<i>CRHT</i>	1.58E+03	2.78E+03
<i>FFLT</i>	-5.96E+03	-5.95E+03
<i>FFRAS1</i>	3.98E+03	4.79E+03
<i>FFRAS2</i>	3.98E+03	5.55E+03
<i>MFHT1</i>	3.52E+03	3.40E+03
<i>MFHT2</i>	3.52E+03	6.55E+03
<i>MFLT1</i>	4.07E+03	3.76E+03
<i>MFLT2</i>	4.07E+03	3.80E+03
<i>MFOF1</i>	4.01E+03	3.66E+03
<i>MFOF2</i>	4.01E+03	6.30E+03
<i>MFRAS1</i>	4.23E+03	5.32E+03
<i>MFRAS2</i>	4.23E+03	7.52E+03
<i>MOLT</i>	1.20E+02	1.20E+02
<i>Ionizing radiation</i> <i>(kBq Co-60 equivalent)</i>		
<i>CRHT</i>	-3.48E+01	-3.45E+01
<i>FFLT</i>	-2.34E+01	-2.35E+01
<i>FFRAS1</i>	4.55E+02	4.77E+02
<i>FFRAS2</i>	4.55E+02	5.36E+02
<i>MFHT1</i>	1.91E+02	2.08E+02
<i>MFHT2</i>	1.91E+02	5.19E+02
<i>MFLT1</i>	-4.43E+01	-3.09E+01
<i>MFLT2</i>	-4.43E+01	-3.09E+01
<i>MFOF1</i>	1.96E+02	2.23E+02
<i>MFOF2</i>	1.96E+02	4.83E+02
<i>MFRAS1</i>	3.01E+02	3.32E+02
<i>MFRAS2</i>	3.01E+02	5.50E+02
<i>MOLT</i>	3.15E+00	3.15E+00
<i>Land use</i> <i>(m²a crop equivalent)</i>		
<i>CRHT</i>	9.81E+02	8.02E+02
<i>FFLT</i>	-7.95E+00	-8.50E+00
<i>FFRAS1</i>	7.35E+03	5.06E+03
<i>FFRAS2</i>	7.35E+03	7.24E+03
<i>MFHT1</i>	2.36E+03	2.03E+03
<i>MFHT2</i>	2.36E+03	5.73E+03
<i>MFLT1</i>	6.42E+03	5.84E+03
<i>MFLT2</i>	6.42E+03	5.85E+03
<i>MFOF1</i>	2.54E+03	1.88E+03
<i>MFOF2</i>	2.54E+03	4.98E+03

<i>MFRAS1</i>	1.89E+03	1.29E+03
<i>MFRAS2</i>	1.89E+03	3.88E+03
<i>MOLT</i>	2.53E+02	2.53E+02
<i>Marine ecotoxicity</i> (kg 1.4-DCB)		
<i>CRHT</i>	7.42E+02	7.45E+02
<i>FFLT</i>	-2.37E+02	-2.37E+02
<i>FFRAS1</i>	6.68E+02	6.22E+02
<i>FFRAS2</i>	6.68E+02	6.60E+02
<i>MFHT1</i>	2.89E+02	2.61E+02
<i>MFHT2</i>	2.89E+02	4.95E+02
<i>MFLT1</i>	2.83E+02	2.38E+02
<i>MFLT2</i>	2.83E+02	2.59E+02
<i>MFOF1</i>	3.06E+02	2.59E+02
<i>MFOF2</i>	3.06E+02	4.55E+02
<i>MFRAS1</i>	6.22E+02	5.95E+02
<i>MFRAS2</i>	6.22E+02	7.58E+02
<i>MOLT</i>	5.53E+00	5.53E+00
<i>Marine eutrophication</i> (kg N equivalent)		
<i>CRHT</i>	-2.16E+01	-1.66E+01
<i>FFLT</i>	8.90E-02	8.91E-02
<i>FFRAS1</i>	7.59E+00	5.31E+00
<i>FFRAS2</i>	7.59E+00	6.78E+00
<i>MFHT1</i>	1.68E+02	1.18E+02
<i>MFHT2</i>	1.68E+02	1.21E+02
<i>MFLT1</i>	4.64E+02	3.96E+02
<i>MFLT2</i>	4.64E+02	3.96E+02
<i>MFOF1</i>	3.29E+01	1.57E+01
<i>MFOF2</i>	3.29E+01	1.77E+01
<i>MFRAS1</i>	3.14E+00	2.24E+00
<i>MFRAS2</i>	3.14E+00	3.85E+00
<i>MOLT</i>	-8.95E+00	-8.95E+00
<i>Mineral resource scarcity</i> (kg Cu equivalent)		
<i>CRHT</i>	6.83E+01	6.84E+01
<i>FFLT</i>	-1.26E+01	-1.26E+01
<i>FFRAS1</i>	2.42E+01	2.30E+01
<i>FFRAS2</i>	2.42E+01	2.89E+01
<i>MFHT1</i>	1.56E+01	1.46E+01
<i>MFHT2</i>	1.56E+01	2.93E+01
<i>MFLT1</i>	2.22E+01	2.03E+01
<i>MFLT2</i>	2.22E+01	2.04E+01
<i>MFOF1</i>	2.00E+01	1.78E+01
<i>MFOF2</i>	2.00E+01	3.01E+01

MFRAS1	1.11E+01	1.39E+01
MFRAS2	1.11E+01	2.42E+01
MOLT	5.25E+00	5.25E+00
<i>Ozone formation, Human health</i> <i>(kg NOx equivalent)</i>		
CRHT	9.47E+00	9.33E+00
FFLT	-4.26E+00	-4.26E+00
FFRAS1	2.01E+01	1.71E+01
FFRAS2	2.01E+01	1.88E+01
MFHT1	3.33E+01	2.65E+01
MFHT2	3.33E+01	3.31E+01
MFLT1	4.50E+01	3.56E+01
MFLT2	4.50E+01	4.01E+01
MFOF1	3.64E+01	2.67E+01
MFOF2	3.64E+01	3.23E+01
MFRAS1	2.19E+01	1.60E+01
MFRAS2	2.19E+01	2.06E+01
MOLT	7.10E-01	7.10E-01
<i>Ozone formation, Terrestrial ecosystems</i> <i>(kg NOx equivalent)</i>		
CRHT	1.01E+01	9.94E+00
FFLT	-4.25E+00	-4.25E+00
FFRAS1	2.10E+01	1.78E+01
FFRAS2	2.10E+01	1.94E+01
MFHT1	3.47E+01	2.76E+01
MFHT2	3.47E+01	3.44E+01
MFLT1	4.72E+01	3.76E+01
MFLT2	4.72E+01	4.21E+01
MFOF1	3.79E+01	2.79E+01
MFOF2	3.79E+01	3.36E+01
MFRAS1	2.30E+01	1.68E+01
MFRAS2	2.30E+01	2.15E+01
MOLT	7.66E-01	7.66E-01
<i>Stratospheric ozone depletion</i> <i>(kg CFC11 equivalent)</i>		
CRHT	-1.15E-01	-9.98E-02
FFLT	-7.98E-02	-7.98E-02
FFRAS1	1.49E-02	1.97E-02
FFRAS2	1.49E-02	3.04E-02
MFHT1	2.53E-02	2.40E-02
MFHT2	2.53E-02	4.61E-02
MFLT1	2.89E-02	2.61E-02
MFLT2	2.89E-02	2.62E-02
MFOF1	2.67E-02	2.37E-02
MFOF2	2.67E-02	4.22E-02

MFRAS1	-1.16E-02	3.16E-03
MFRAS2	-1.16E-02	1.86E-02
MOLT	1.15E-04	1.15E-04
<i>Terrestrial acidification</i> (kg SO ₂ equivalent)		
CRHT	6.08E+01	6.64E+01
FFLT	-7.39E+00	-7.31E+00
FFRAS1	3.51E+01	3.02E+01
FFRAS2	3.51E+01	3.53E+01
MFHT1	4.26E+01	3.56E+01
MFHT2	4.26E+01	5.77E+01
MFLT1	6.24E+01	5.18E+01
MFLT2	6.24E+01	5.65E+01
MFOF1	5.19E+01	4.02E+01
MFOF2	5.19E+01	5.87E+01
MFRAS1	5.26E+01	4.62E+01
MFRAS2	5.26E+01	6.17E+01
MOLT	5.54E-01	5.54E-01
<i>Terrestrial ecotoxicity</i> (kg 1,4-DCB)		
CRHT	8.99E+03	1.03E+04
FFLT	-1.02E+04	-1.02E+04
FFRAS1	1.42E+04	1.38E+04
FFRAS2	1.42E+04	1.66E+04
MFHT1	1.01E+04	9.22E+03
MFHT2	1.01E+04	1.70E+04
MFLT1	2.42E+04	2.18E+04
MFLT2	2.42E+04	2.20E+04
MFOF1	1.06E+04	8.82E+03
MFOF2	1.06E+04	1.53E+04
MFRAS1	8.27E+03	9.41E+03
MFRAS2	8.27E+03	1.48E+04
MOLT	7.01E+02	7.01E+02
<i>Water consumption</i> (m ³)		
CRHT	9.82E+00	8.13E+00
FFLT	-1.55E+01	-1.56E+01
FFRAS1	5.34E+02	4.06E+02
FFRAS2	5.34E+02	5.67E+02
MFHT1	1.97E+02	1.79E+02
MFHT2	1.97E+02	5.00E+02
MFLT1	4.78E+02	4.29E+02
MFLT2	4.78E+02	4.30E+02
MFOF1	2.24E+02	1.86E+02
MFOF2	2.24E+02	4.54E+02

MFRAS1	1.75E+02	1.51E+02
MFRAS2	1.75E+02	3.75E+02
MOLT	6.35E+00	6.35E+00

Table S6: Characterized results of the sensitivity analysis on feed for freshwater fishes in concrete ponds

<i>Year</i>	<i>New value</i>		<i>Baseline value</i>	
	2017	2040	2017	2040
<i>Acidification</i>	4.44E+02	4.44E+02	-7.56E+00	-7.50E+00
<i>Climate change, short term</i>	4.17E+04	4.17E+04	-2.66E+03	-2.66E+03
<i>Eutrophication</i>	5.51E+02	5.51E+02	-5.66E+00	-5.63E+00
<i>Fossil and nuclear energy use</i>	3.30E+05	3.30E+05	-1.23E+04	-1.23E+04
<i>Freshwater ecotoxicity</i>	4.20E+08	4.22E+08	-1.44E+07	-1.41E+07
<i>Human toxicity cancer</i>	3.36E-03	3.36E-03	-5.86E-05	-5.83E-05
<i>Human toxicity non cancer</i>	2.85E-02	2.85E-02	-8.20E-04	-8.20E-04
<i>Land competition</i>	1.17E+04	1.17E+04	2.28E+02	2.26E+02
<i>Mineral resources use</i>	6.09E+03	6.09E+03	3.75E+01	3.75E+01
<i>NPPU</i>	0.00E+00	0.00E+00	0.00E+00	0.00E+00
<i>Water scarcity</i>	-8.61E+05	-8.61E+05	-1.06E+03	-1.06E+03

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PAPER V

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

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

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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 pillar 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. 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, important aquaculture growth has in general been limited to low- to middle-income countries, and despite multiple attempts to implement policies aimed at boosting it, high-income countries have had difficulties to trigger their aquaculture revolution (Abate et al., 2016; Anderson et al., 2019; Costa-Pierce, 2010; FAO, 2016).

Studies have shown that countries with strict environmental regulations, as most high-income countries, often experienced delayed growth of the aquaculture sector because of a lack of technically-viable solutions for more environmental-friendly aquaculture technologies, or the lack of quantitative assessments providing proofs of the environmental benefits of such technologies (Abate et al., 2018, 2016). These regulations are necessary for preserving the biodiversity, because despite its indisputable socioeconomic advantages, aquaculture production has been found to have various negative impacts on the environment. It affects local ecosystems, due to e.g. 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. 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 policy 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). Multiple LCA studies can be found for individual farms, existing commercial ones as well as pilot projects, but sectorial LCA studies are rare for aquaculture so far and usually limited to specific species, e.g. assessment of the current impacts of the mussel production sector in Spain by Iribarren et al. (2010). A noticeable exception is 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), and were the only ones to also take a prospective angle.

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 realistic, policy-based scenarios. As 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. In the following section, the framework is introduced and its main features described, before being applied to the two case studies described in Section 2. 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 contains 4 main steps illustrated in Figure 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. 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 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. 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 socioeconomic 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, imports and exports as well as the production. Such modeling has been done by Tran et al. (2017) and Bohnes et al. (2020, under revision), and we therefore invite the reader to refer to these papers for details about the methodology (see also the obtained scenarios for Singapore and Norway in Sections 2.2.1 and 2.2.2, respectively). So far, such existing models do not contain a comprehensive environmental impact assessment module. Therefore, Step 3 consists of generating the evolution 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 categories need to be built, including the modeling of their evolution through the considered reference time period. All relevant production elements have to be included (i.e. production, feed, infrastructures, consumables and post-farming – see Figure 1). Data need to be aggregated in country representative processes, and to be time-differentiated to reflect potential technology optimization and expected changes in farmers' habits along the period, including feed selection (Figure 1). An extensive set of environmental impact categories should be assessed, including toxicity impacts, resource use impacts and biomass extraction as recommended (Bohnes and Laurent, 2019). Finally, in Step 4, the results of the LCA are interpreted considering the limitations and uncertainty of the study.

Figure 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.

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, 2019a). Aquaculture is no exception and the country farmed less than 6000 tons of seafood in 2017 (FAOSTAT, 2019). Therefore, despite scoring among the highest in food security index worldwide thanks to its strong economy, Singapore is also found to be highly vulnerable to external risks when it comes to food supply (The Economist Group, 2018). This means that in case of a natural, climatic, economic or political crisis, the city-state's supply in food could easily be threatened. In that context, the Singaporean government announced a new food policy named the “30-by-30”, which aims at increasing to 30% the proportion of its consumption provided by domestic production by 2030. Therefore, this case study aims at analyzing the implications of this policy during and post implementation, hence the choice of 2017-2040 as 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. Systems referred to as “low-tech” require on average lower inputs than “high-tech” ones, by e.g. having lower energy requirements but also by using rainwater for their freshwater needs. In these systems, limited technical knowledge on fish growth is used and therefore they have in general higher feed conversion ratio (FCR). They usually use poorly adapted dry feed pellets or by-products from food industry as feed, which contributes to even higher FCR. In open systems, seafood is farmed directly in natural water bodies, hence contributing to eutrophication via emissions of nutrients during production, due to uneaten feed and feces. On the other hand, closed systems use confined spaces where the nutrients can be collected as a sludge during cleaning. This sludge is then either used as natural fertilizer in local agriculture companies or disposed of in landfills.

In several literature reviews, feed has been identified as the most contributing element to environmental impacts of aquaculture systems (Bohnes et al., 2019; Henriksson et al., 2012). Among the most important issues is the use of marine resources in the ingredients (Kristofersson and Anderson, 2006; Naylor et al., 2009). Two different strategies have been considered to reduce this dependence on wild capture: reducing

the use of fresh fish in fishmeal and fish oil (FMFO) production and reducing the use of FMFO in the diet. The former is already a trend in most feed manufacturing companies as it reduces the costs of FMFO as well as the environmental impacts (as e.g. EWOS, 2015 and Cargill, 2017). When it comes to replacing FMFO by other ingredients, several possibilities have been raised such as plant-based ingredients, waste from the food industry or novel feed. For instance, in the salmon farming industry, the use of FMFO has been reduced from 90% to 30% between 1990 and 2013, replaced by plant-based ingredients such as soybean meal and rape oil (Fiskeridirektoratet, 2013). However, it is not clear whether plant-based ingredients are suitable to replace FMFO to such high levels for all seafood species without influence the growth (see e.g. Sourabié et al., 2018). Therefore, some novel ingredients such as insect-based and algae-based meals/oils are seen as promising too because they are often part of the natural diet of the fishes, contrarily to plant-based ingredients (Burr et al., 2012; Shah et al., 2017). We thus decided to assess two different Feed options that reflect the two identified 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.

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

Because Singaporean aquaculture was never assessed before with LCA and due to the low amount of LCAs on Asian fish farming in general, the optional step O was conducted to give an overview of the environmental impacts of the different production categories in 2017 and 2040. The results of this analysis as well as the corresponding LCIs are presented in Bohnes and Laurent (2020, submitted).

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 development and construction of the scenarios is available in Bohnes et al. (2020, under revision). 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 in order 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 the future technologies (Figure 2).

Figure 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.

2.2.2 Norway in the reign of salmon

Norway is a powerful actor on the international seafood production stage, 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 world leader in salmon production, yet within a sustainable framework (Norwegian Ministries, 2019). The salmon industry currently faces several challenges and its growth is deemed compromised if solutions are not implemented to address them soon (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 Ministries, 2019). The case study aims at assessing the environmental impacts of these two approaches of the Norwegian government.

Norwegian aquaculture is limited to few species and consists of almost 95% of Atlantic salmon, for which Norway is the production and export world leader (FAOSTAT, 2019a). 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, salmonids and mollusks in integrated multi-trophic aquaculture (IMTA) is another innovative technology that is likely to develop 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.

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

Based on the incentive scheme of the Norwegian government, we developed 3 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 of the production of salmonids due to a quick reduction of environmental issues and a diversification of technologies. Scenario 2 (NO-S2) portrays a 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 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 Figure 3.

Figure 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 that SAOF, SAINT, WFSC and MOINT are not visible on the graphs due to their low proportions relative to SASC and SARAS.

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 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. Looking only 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 Figure 1 (Step 3) and contains 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 retailer and to consumer, retailing 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 multifunctional processes that deliver more than one output of which not all are used in the analyzed system is 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 fertilizer is modeled using system expansion with avoided production of synthetic fertilizer. Algal oil production has 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 manufacturing, and are modelled as waste and therefore associated to no burden. 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 a synthesis of key modeling aspects are summarized.

For the Singapore case study, primary data was collected from farms using a questionnaire addressing all elements at farm level, i.e. feed composition and FCR, production characteristics, equipment, infrastructures and use of consumables, energy, water and fingerlings as well as their origin. Then, data from individual farms were aggregated based on their yearly production and on expert judgment to produce country-representative inventories for the 5 existing production categories included in this study. The inventories are available in Bohnes and Laurent (2020, submitted). 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. 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).

For the Norway case study, data were gathered from literature and governmental reports to build inventories representative of Norwegian aquaculture for the 6 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 on Reid et al. (2008) and the typical mussels/salmon ratio of such a production site 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 fingerlings from Norway, as these are the most common origin of these goods (Winther et al., 2009). To transform live-weight mass at farm gate to mass of edible seafood, an edible ratio that varies between different species groups is used and is 0.62 for salmonids, 0.36 for white fishes and 0.25 for mollusks (blue mussels as reference) (FAO, 2019a,b; 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 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.

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

Change type	Parameter/process impacted	Change within 2017-2040	
		Singapore	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 (<i>FO</i>) 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.

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 global 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 AoPs are Ecosystems quality and Human health. They are all listed with their corresponding unit 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 (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, Skretting and Cargill - 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 THE FUTURE OF SINGAPOREAN AQUACULTURE

Figure 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 Figure 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.

Figure 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 the 18 impact categories of IMPACT World+ midpoint and NPPU (net primary production use) (A to S) and the 2 areas of protection of IMPACT World+ endpoint (T and U).

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 minimum 80% of the yearly production during the whole period (see Figure 2), and is hence likely to drive the normalized impacts. This technology for marine fishes is between mature and obsolete, and optimization potential is low, so the impacts per ton of edible marine fish produced show little variation 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 a 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 of 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 in general due to the 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-CO₂eq/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-CO₂eq per ton of live-weight seafood produced, corresponding roughly to 6-30 t-CO₂eq/ton-edible-seafood produced (with 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 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, an open system that has a high FCR, and therefore has the highest eutrophication impacts of all production categories included in the study (Bohnes and Laurent, 2020 submitted). Otherwise, SG-S2 has impacts 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 are quite low in Singapore compared to past studies.

Land 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 stays relatively stable with Feed option 2 with small influence of the scenarios. Indeed, the proportion of marine fishes in “low-tech” decreases with time, a category that 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 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 regards 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 evolution 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, under review) 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 ionizing radiations 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 by trimmings in FMFO production is a more environmental-friendly option than replacing FMFO by 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 THE FUTURE OF NORWEGIAN AQUACULTURE

Figure 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 Figure 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.

Figure 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 the 18 impact categories of IMPACT World+ midpoint and NPPU (net primary production use) (A to S) and the 2 areas of protection of IMPACT World+ endpoint (T and U).

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 a 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 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 scenarios. Normalized impacts of both Ecosystems quality and Human health increase much more with Feed option 2 than Feed option 1 over time. Ecosystem quality is dominated by freshwater ecotoxicity while Human

health is dominated by climate change long term, 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 CO₂-eq per ton of edible seafood produced through 2017-2040, which is comparable to the 4-7 tons CO₂-eq per ton of edible salmon found by Liu et al. (2016) but a bit higher than the 2.5-4 tons CO₂-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 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 has no emissions of N/P in open waters during production. Feed option strongly influences the results as 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 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 of the electricity mix through the time-scope engendered substantial changes in the 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 uncertainty 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 Method). 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). 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. RAS also seems to have interesting environmental characteristics compared to sea cages for salmonids, as it has 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 by the introduction of advantages in terms of 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, 2020 submitted). Increasing the proportion of trimmings in FMFO manufacturing was found to have the lowest environmental impacts in general 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 final product than when based on fresh fish. Indeed, using trimmings implies little influence on the type of fish and the parts of the fish that are reduced, and 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 effect on eutrophication. This impact is often considered as 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 emission 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 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 a high electricity consumption, which in the case of both Singapore and Norway meant high human health impact at damage level. This can be overturned if the algae production improves by reducing its energy needs, or in Singapore if the electricity mix becomes more environmental friendly. 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 gut microbiome can help to 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 the 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 in this study. Therefore, the diet that is at the same time nutritious for the fishes and engender the lowest environmental impacts is still to be determined.

5.2 CLIMATE CHANGE MITIGATION POTENTIAL

Both countries have set climate change mitigation targets for 2030 as follow-up to the Paris Agreement of the COP 25. 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 (MEWR, 2018). When it comes to the first goal, 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 when they contribute to consumption that occurs 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 2030, as illustrates Figure 6. Indeed, the total production increases several fold until 2030 to fulfill the government’s goal in terms of self-sufficiency, which will also contribute to increasing total climate change impacts of that specific sector.

On the other hand, Norway wants to reduce all its greenhouse gas emissions by 40% before 2030 (The Mission, 2019). 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 is increasing in all scenarios, the total climate change impacts of the aquaculture sector will increase as well until 2040, as illustrated in Figure 7.

Therefore, it seems that both Singapore and Norway cannot rely on the aquaculture sector to reach their GHG reduction goals as defined in the Paris agreements if they persevere with the implementation of their new aquaculture policies and the resulting increase in production. They will both need to decrease more drastically the emissions from other sectors to offset that increase from aquaculture.

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

Figure 7: Yearly total climate change impacts from 2017 to 2040 for the 3 scenarios and the two Feed options in Norway, with the total production of edible seafood on the secondary axis in tons per year.

5.3 ECO-EFFICIENCY VS. ECO-EFFECTIVENESS

However, the increase in domestic production of seafood might contribute to change Singaporean and Norwegian food habits, and increase their consumption of seafood to the disadvantage of other animal proteins (Bohnes et al., 2020 submitted and Supplementary Methods). Despite not being environmentally neutral, aquaculture production has been found to have 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 CO₂-eq per ton of edible beef produced (considering an edible fraction of 41% - University of Tennessee Institute of Agriculture, 2019), which is at least twice more than our highest results. Salmon in particular has been found to be associated with the lowest greenhouse gases emissions per calories content (Hilborn et al., 2018). Therefore, taking a substitution of meat with seafood into account, aquaculture production might not participate to reducing climate change eco-efficiency, but may increase the eco-effectiveness of the food system in general, as it might encourage 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.

5.4 LESSONS LEARNED AND RELEVANCE OF THE PROPOSED FRAMEWORK FOR POLICY-MAKING

Recommendations to decision-makers can be made on various aspects touching aquaculture development. For example, according to the Norwegian study, the industry forecasts for 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, expressed as high subsidies 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 this 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 on shore) to innovative technologies (such as RAS or offshore aquaculture) would create. Additionally, the study offers the first environmental impacts baseline for Singaporean aquaculture as reference of comparison for new systems when assessing them with LCA.

5.5 OPERABILITY OF THE FRAMEWORK AND FURTHER RESEARCH NEEDS

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. However, in order to improve its reliability and accessibility to future practitioners, the following aspects should be addressed:

- 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 transform other data to adapt it 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 more user-friendly economic model due to the expert knowledge required in applying the framework. 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.
- Integration of an absolute environmental sustainability module in partial equilibrium 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, 2015).
- Implementation of a life cycle sustainability assessment (LCSA). Only the environmental dimension of sustainability is assessed in the current framework, despite the importance of 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 would account for economic impacts such as profitability, productivity or business diversity. These impacts are particularly relevant to assess in large-scale studies like this one due to the extent of the economic and social changes it can engender.

- 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 a regulatory pressure on aquaculture systems for management optimization. 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.

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SUPPLEMENTARY INFORMATION A: SUPPLEMENTARY METHODS

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

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Table of Contents

1	Scenarios for aquaculture development in Norway	2
1.1	Seafood production industry in Norway	2
1.2	Potential seafood production in the future	3
1.3	Scenarios definition	4
1.4	Adaptation of the AsiaFish model	6
1.5	Results and discussion	9
1.6	Conclusion	16
2	Life cycle assessment application	18
2.1	Life cycle impact assessment	18
2.2	Data sources and Assumptions	19

1 SCENARIOS FOR AQUACULTURE DEVELOPMENT IN NORWAY

Abbreviations:

SASC	Salmons from sea cages
SACAP	Salmons from capture
SAINT	Salmons from IMTA
SARAS	Salmons from RAS
SAOF	Salmons from offshore systems
WFCAP	White fishes from capture
WFSC	White fishes from sea cages
OFCAP	Oily fishes from capture
MOCAP	Mollusks from capture
MOINT	Mollusks from IMTA
CRCAP	Crustaceans from capture
RAS	Recirculating aquaculture system
IMTA	Integrated multi-trophic aquaculture
Proc	Processed fish

1.1 SEAFOOD PRODUCTION INDUSTRY IN NORWAY

Norway is an important producer in both capture and aquaculture, and is the second biggest exporter of seafood in the world (FAO, 2016). Producing seafood is strongly anchored in the local culture for generations and the techniques and technologies used are among the most efficient in that industry globally. Norwegian capture fisheries cover a wide range of species, going from crustaceans to codfishes, with an emphasis on pelagic fishes such as herring and mackerel (FAOSTAT, 2019b). On the contrary, Norwegian aquaculture is limited to few species and consists for almost 95% of Atlantic salmon, for which they are the production and export world leaders (FAOSTAT, 2019a). 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). An analysis of the literature revealed that RAS and offshore aquaculture have a potential for development in the future Norwegian aquaculture systems. Additionally, integrated multi-trophic aquaculture (IMTA) raises as another technology that is likely to develop 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 reduces the cost of production by reducing the feed need

(Wang et al., 2012). In the case of Norway, the most promising opportunity seems to be the combination of Atlantic salmon, mussels and algae. Algae are not included in this study, therefore only mollusks and salmons are integrated into the model. Table A1 illustrates the different technologies used for each of the 11 categories of seafood considered in the model, and Table A2 gathers the descriptions of all technologies used in Norwegian current and future aquaculture.

Table A1: Norwegian seafood production categories with species and technologies (RAS = recirculating aquaculture system; IMTA = integrated multi-trophic aquaculture)

	Salmons, trout and chars	White fishes	Oily fishes	Mollusks	Crustaceans
Capture	SA-CAP	WF-CAP	OF-CAP	MO-CAP	CR-CAP
Aquaculture – sea cages	SA-SC	WF-SC			
Aquaculture – RAS	SA-RAS				
Aquaculture – offshore	SA-OF				
Aquaculture – IMTA	SA-INT			MO-INT	

Table A2: Description of the technologies currently used and likely to develop in Norway aquaculture industry.

Implementation status	Technologies	Description
Current	Sea cages	On-land recirculating water systems for the production of juveniles and large cages in the sea for the grow-out stage
Future	Recirculating aquaculture system (RAS)	Entirely optimized systems where the water is treated and reused many times (can be used for the production of any type of seafood).
Future	Offshore aquaculture	Structures such as cages in the sea that are built far from the shore.
Future	Integrated multi-trophic aquaculture (IMTA)	Aquaculture technique where several species from different trophic levels are grown right next to each other in order to optimize the use of nutrients.

1.2 POTENTIAL SEAFOOD PRODUCTION IN THE FUTURE

Norway is already a powerful actor on the international seafood production stage, and the Norwegian government intend to maintain this status with a continually growing seafood sector. In that context, authorities are determined to keep their position of world leader in salmon production, yet within a sustainable framework (Norwegian Ministries, 2019). The salmon industry currently faces environmental challenges and its growth cannot maintain its current levels if a solution is not found in the coming years (Lekang et al., 2016). A challenging control of diseases, in particular sea lice, and escapes are the main problems of Norwegian aquaculture now (Lekang et al., 2016). The Norwegian government considers two complementary approaches to tackle that issue. First, the government is committed to facilitating the sustainable development of new technologies that would solve these problems (Norwegian Ministries, 2019; Norwegian Ministry of Fisheries and Coastal Affairs, 2009).

Second, the Norwegian government discusses the opportunity of diversifying aquaculture production by introducing other species than salmon and trout (Norwegian Ministries, 2019). Both were expected to lower or suppress the typical environmental pressures of current Norwegian aquaculture, and therefore both solutions would help the Norwegian seafood industry to become a worldwide example of sustainability, according to the ministries. Finally, capture fisheries should remain an important source of revenue but more regulations will be implemented in order to ensure a sustainable use of the fish stocks, which will allow Norway to stabilize its current production level with no further increase (Norwegian Ministries, 2019).

Based on expected government policies, the Norwegian industry made estimations about the future growth of aquaculture. Salmon production is expected to reach 3 million tons in 2040, with an average annual increase of 3 to 4% maximum concerning the current production technologies (Olafsen et al., 2012). However, this is only possible if the environmental issues currently faced by salmon aquaculture are solved. Otherwise, the increase of salmon would be lower due to a limited amount of licenses given by the government (Olafsen et al., 2012). The introduction of new species is additionally expected, consisting mainly of cod, and shellfish from IMTA with salmon, and is anticipated to reach an annual production of 30000 and 2000 tons in 2030, respectively (Olafsen et al., 2012).

1.3 SCENARIOS DEFINITION

- *Business-as-usual scenario (NO-BAU)*: strong salmon-based aquaculture using the current technology thanks to the environmental issues assumed to be solved progressively: annual increase of 3% of salmon production in sea cages over the whole period. No increase in the other categories.
- *Scenario 1 (NO-S1)*: important increase of the production of salmon and trout due to a quick reduction of environmental issues and a diversification of technologies: annual increase of 4% of salmon production in sea cages over the whole period, associated with an important increase of salmon production in RAS and offshore technologies of 20% annually during the whole period. IMTA is a lesser priority, hence an increase of 15% annually during the whole period.
- *Scenario 2 (NO-S2)*: species diversification and limited increase of the production of salmon and trout in sea cages due to a slow reduction of environmental issues. Annual increase of 2% of salmon production in sea cages over the whole period. Introduction of white fish production in sea cages and mollusks in IMTA with salmons, with an annual increase of 5% for the former and 25% for the latter until 2040, and lower growths afterwards. Moderate increase of RAS and offshore (10% annually, or half of NO-S2).

Note that the IMTA production of salmons and mollusks should always follow the same patterns. No increase of capture fisheries is implemented any of the scenarios (already assumed to be at their maximum sustainable level).

Table A3: Percentage of change each year for the 3 scenarios (in % compared to the previous year)

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Business-as usual																								
SASC	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
SARAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAOF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAINT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SACAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WFSC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOINT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scenario 1																								
SASC	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SARAS	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
SAOF	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
SAINT	0	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
SACAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WFSC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOINT	0	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scenario 2																								
SASC	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
SARAS	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
SAOF	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
SAINT	0	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
SACAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WFSC	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
WFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OFCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MOCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOINT	0	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
CRCAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1.4 ADAPTATION OF THE ASIAFISH MODEL

Figure A1 presents the 11 different supply categories, differentiated by species and technology, and the corresponding 5 demand categories, differentiated by species only.

Figure A1: Structure of the AsiaFish model adapted for Norway, with the different supply, demand and matching categories, i.e. trade (RAS= recirculating aquaculture system; IMTA= integrated multi-trophic aquaculture).

The reference year in the model is 2017. Seafood production and consumption data as well as general data concerning Norway, such as population and expenditure, were retrieved from Statistics Norway (SSB, 2019). Imports and exports quantities and prices were obtained through private communication with the Norwegian Seafood Council, and the values of capture and aquaculture were obtained in Fiskeridirektoratet reports (Fiskeridirektoratet, 2013a, 2013b; Norwegian Seafood Council, 2019). Algae, sharks, aquatic mammals, rays and cephalopods were disregarded from the study because their aquaculture production is negligible compared to the other species of the study (less than 1% in quantity – FAOSTAT, 2019a,b). Domestic demand corresponding to local production of non-food products (i.e. aquafeed) is removed from the balances because only human consumption is considered in this study. Tables A5 and A6 present the seafood balance in terms of quantity and value for Norway in 2017.

Concerning the demand, supply and expenditure elasticities differentiated by species' categories, a review of the literature was conducted on Norway and the European countries at large (because of the integration of the European market for some species – Nielsen et al., 2009). Several own-price demand elasticities for salmon were retrieved in recent studies for Norway, and the average was thus considered

(Brækkan, 2014; Xie et al., 2009) Regarding the other species, no own-price demand elasticities were available specifically for Norway. However, the European market is integrated for some species such as white and oily fishes. Therefore, elasticities from the UK were used for these species (Fousekis and Revell, 2005; Tiffin et al., 2011). An own-price demand elasticity for crustaceans in the European Union was considered because of the absence of value specific to Norway (Asche et al., 1997). Regarding mollusks, no study were found from Nordic or even European countries, and therefore a general elasticity for seafood in Norway was selected as proxy (Muhammad et al., 2012). Expenditure elasticities were found for the Nordic countries for all fresh species and for Norway for processed fish (Cai and Leung, 2017; Muhammad et al., 2012). All cross-price demand elasticities were set to 0 because the seafood products are considered non-substitutable, nor complementary. All the supply elasticities are also set to 0 because the quantities produced are either independent from the price due to the intrinsic nature of the supply (case of fish capture) or more dependent on other factors than the price (for aquaculture). All elasticities are summarized in Table A4.

Table A4: Elasticities used in the Asiafish model for Norway

Species	Own-price elasticity	Expenditure elasticity	Demand cross-price elasticity
			Supply elasticity
Salmons	-0,716	0,4763	0
White fish	-0,688	0,6062	0
Oily fish	-0,46	0,6062	0
Mollusks	-0,267	1,0826	0
Crustaceans	-0,762	1,2537	0
Processed fish	/	0,364	0

Table A5: Seafood balance for Norway in 2017 in quantity (tons), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories.

	Salmons					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
	Sea cages	RAS	Offshore	IMTA	Capture	Sea cages	Capture	Capture	Capture	IMTA	Capture	
<i>Production</i>	1,290,376	13,058	0	0	2,112	1,623	812,704	791,955	4,286	0	23,589	1,234,735
	Salmons					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
<i>Consumption</i>	22,209					102,409		857	4,148		448	164,762
<i>Export</i>	861,920					245,720		79,027	553		1,350	1,169,262
<i>Import</i>	290					332		144,388	477		181	99,289
<i>Intermediate</i>	421,968					466,530		856,459	85		21,971	-

Table A6: Seafood balance for Norway in 2017 in value (thousands of US dollars), including production, consumption, exports, imports and intermediate demand (aimed at producing processed fish) for the 12 supply categories and the 6 demand categories.

	Salmons					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
	Sea cages	RAS	Offshore	IMTA	Capture	Sea cages	Capture	Capture	Capture	IMTA	Capture	
<i>Production</i>	10,570,912	97,346	0	0	17,283	3,793	1,899,476	834,391	8,962	0	185,259	6,805,529
	Salmons					White fishes		Oily fishes	Mollusks		Crustaceans	Processed fish
<i>Consumption</i>	237,948					266,820		974	7,088		3,308	1,849,735
<i>Export</i>	5,929,634					424,448		38,400	4,172		25,624	5,507,766
<i>Import</i>	1,119					3,509		178,282	2,397		5,774	551,973
<i>Intermediate</i>	4,521,004					1,215,511		973,299	145		162,101	-

1.5 RESULTS AND DISCUSSION

Figure A2 presents the evolution of Norwegian seafood production, consumption and trade from 2017 to 2040 according to the BAU and the two explorative scenarios. Norway remains a strong seafood exporter in all scenarios, with imports being negligible compared to domestic production (hence not visible in Figure A2). The production of fresh fish increases during the studied period in all scenarios, but the production of processed fish remains quite constant. When considering fish farming in particular, Norwegian aquaculture production increases from 1 million tons in 2017 to 2.5, 4 and 2.1 million tons in 2040 in the NO-BAU, NO-S1 and NO-S2 scenarios, respectively. The important difference between NO-S1 and the two other scenarios mainly comes from the difference in production of salmon from RAS and offshore (Figure A3). The growth in sea cage production depends on the rapid solving of the environmental issues (e.g. sea lice), thus highlighting the importance of that issue for the overall Norwegian production. The expected total production of fresh fish of 3 million tons is reached only in NO-S1, but all scenarios present a final aquaculture production in 2040 within the range expected by the Norwegian Industry (i.e. 2-4 million tons - Olafsen et al., 2012). The dramatic increases in production, particularly in NO-S1, may suggest that Norway could remain an important player internationally and thus meet its objective to be one of the key seafood exporting countries in the world.

Figure A2: Total domestic production, consumption and imports of fresh fish and processed fish in Singapore for the three scenarios during the period 2017-2040; the difference between the total domestic demand and the cumulated stacked curves equals the exports.

Figure A3: Domestic aquaculture production for each of the species and technologies and for the 3 scenarios, and the years 2017, 2030 and 2040 (LOGARITHMIC SCALE)

In scenario NO-BAU, the aquaculture production remains exclusively salmon in sea cages along the whole period (Figure A3). In scenario NO-S1, an important production of salmon from RAS appears around 2030 and increases until accounting approximately 15% of the total production in 2040 (Figure A3). Production of other species than salmon is almost inexistent in this scenario. NO-S2 undertakes a lower development of innovative technologies for salmon, and production of white fish and mollusks in IMTA begins to appear along the period, although their combined proportion reaches only 0.4% of aquaculture production in 2040. The predicted production of white fish does not cross the threshold of 30000 tons/yr expected in 2030 by the industry, from far. With the current level of increase, white fish production reaches only 3000 tons/yr in 2030 and 5000 tons/yr in 2040. A faster increase in this production type would be needed to reach the estimates of the industry, which is unlikely according to the authors' expert opinions. This may be because these estimates are outdated, as they were produced in 2012 when the cod farming industry was still benefiting from an impressive yearly increase. Between 2010 and 2015, Norwegian cod farming decreased from 21000 tons/yr to 4 tons/yr because of various production issues such as high larval mortality rates and important escapes levels that could not be addressed (Brown et al., 2003; Moe et al., 2007; SSB, 2019). Therefore, even though white fish aquaculture seems to be increasing again in Norway as some solutions have been found (1600 tons/yr in 2017), reaching 30000 tons/yr seems too optimistic. Production of mollusks in IMTA attains 3600 tons/yr in 2040, but is only at 300 tons/yr in 2030, and therefore does not exceed the estimate of the industry in that year (i.e. 2000 tons/year). The second objective of the Norwegian government was to develop aquaculture in a way they define as sustainable, i.e. whether by developing and implementation other technologies than the traditional sea cages or encouraging species diversification, and none of these is fulfilled by the any of the scenarios.

It should be kept in mind that the AsiaFish model is not a forecast model. Thus, some of the aforementioned quantities from the model should be taken with caution, as the trends and tendencies are the main outputs to be analyzed from the model.

Figure A4: Annual distribution for each of the species and technologies and for the 3 scenarios, and the years 2017, 2030 and 2040

The evolution of the prices according to the model seems reasonable, with maximum one order of magnitude difference between 2017 and 2040. The price of salmon is decreasing in all scenarios (-19% in BAU, -33% in NO-S1 and -18% in NO-S2), translating the higher availability of this product. It is good for the Norwegian aquaculture, as lower prices will facilitate the exports to countries that might not be able to afford Norwegian salmon now. Prices of white fishes increase by 23% in BAU, 26% in NO-S1 and 45% in NO-S2. Prices of oily fishes and crustaceans increase in all scenarios as well, as its supply does not increase and therefore becomes a rarer product compared to salmon that increase a lot. Prices of mollusks increase in BAU, as its production stays stable, but decrease in NO-S2 where

production of mollusks in IMTA increases a lot, following therefore the same logic than the other products stated above. Prices of processed fish remain quite stable in all scenarios.

Finally, this increase in production induces an increase in the households' consumption of seafood as it can be seen in Table A7.

The comprehensive results concerning production are available in Table A8 for all the included production categories.

Figure A6: Prices of domestic production for each species and technology for the 3 scenarios, and the years 2017, 2030 and 2040

Table A7: Household consumption of the different fish types [000 tons] for the 3 scenarios.

Scenario BAU						
Year	Salmonids	White fishes	Oily fishes	Mollusks	Crustaceans	Processed
2017	22,20884	102,409	0,85732	4,14792	0,4484	164,7624
2018	22,54899	102,7485	0,86059	4,174	0,44893	165,9708
2019	22,90535	103,08	0,86378	4,19254	0,44929	167,4095
2020	23,26769	103,4102	0,86694	4,21036	0,44963	168,876
2021	23,63622	103,7388	0,8701	4,22749	0,44996	170,3712
2022	24,01023	104,0665	0,87324	4,24443	0,45028	171,8804
2023	24,39004	104,3929	0,87638	4,26108	0,4506	173,4072

2024	24,77507	104,7187	0,87952	4,27779	0,45092	174,9401
2025	25,1825	105,0327	0,88249	4,28651	0,45105	176,7621
2026	25,57923	105,3564	0,88562	4,30319	0,45137	178,3184
2027	25,98187	105,6791	0,88874	4,31977	0,45169	179,8878
2028	26,39054	106,0008	0,89187	4,33624	0,452	181,4703
2029	26,80536	106,3215	0,89499	4,35261	0,45231	183,0662
2030	27,22643	106,6411	0,89812	4,3689	0,45262	184,6756
2031	27,65389	106,9597	0,90124	4,38511	0,45293	186,2986
2032	28,08786	107,2772	0,90436	4,40123	0,45324	187,9355
2033	28,52847	107,5937	0,90749	4,41729	0,45354	189,5864
2034	28,97587	107,909	0,91062	4,43328	0,45384	191,2515
2035	29,43017	108,2233	0,91375	4,4492	0,45414	192,931
2036	29,89153	108,5364	0,91689	4,46507	0,45443	194,625
2037	30,3601	108,8484	0,92002	4,48089	0,45473	196,3337
2038	30,83602	109,1593	0,92317	4,49665	0,45502	198,0573
2039	31,31945	109,469	0,92631	4,51237	0,45531	199,796
2040	31,81038	109,7777	0,92947	4,5281	0,4556	201,5479
Scenario 1						
Year	Salmonids	White fishes	Oily fishes	Mollusks	Crustaceans	Processed
2017	22,20884	102,409	0,85732	4,14792	0,4484	164,7624
2018	22,62081	102,7871	0,86103	4,19102	0,44929	165,6441
2019	23,05232	103,159	0,86468	4,22609	0,44998	166,7601
2020	23,51577	103,5149	0,86813	4,248	0,45036	168,3066
2021	23,99107	103,8693	0,87156	4,2696	0,45072	169,8864
2022	24,47788	104,2232	0,87499	4,29163	0,45108	171,4796
2023	24,97961	104,5748	0,87839	4,31296	0,45141	173,1287
2024	25,57285	104,8751	0,88106	4,29929	0,45089	176,0231
2025	26,0464	105,2624	0,885	4,34828	0,45185	176,8041
2026	26,59762	105,6098	0,88836	4,37011	0,45214	178,5697
2027	27,15732	105,9632	0,89183	4,39674	0,45251	180,2191
2028	27,73694	106,3163	0,8953	4,42417	0,45288	181,9006
2029	28,3368	106,6704	0,8988	4,45325	0,45326	183,5922
2030	28,95925	107,0257	0,90233	4,48416	0,45364	185,2967
2031	29,60667	107,3826	0,9059	4,51722	0,45403	187,0129
2032	30,28182	107,7415	0,90951	4,55281	0,45443	188,74
2033	30,98792	108,1029	0,91317	4,59133	0,45483	190,4773
2034	31,72868	108,4675	0,91689	4,63325	0,45525	192,2239
2035	32,4136	108,8926	0,92157	4,7057	0,45625	192,9274
2036	33,44509	109,1464	0,92356	4,69886	0,45548	196,949
2037	34,04355	109,6824	0,93004	4,82687	0,45745	195,841
2038	35,31072	109,8789	0,93111	4,80311	0,45619	201,0183
2039	35,86227	110,5192	0,93931	4,97877	0,4588	198,515
2040	37,47674	110,624	0,93889	4,92815	0,45688	205,3796
Scenario 2						

Year	Salmonids	White fishes	Oily fishes	Mollusks	Crustaceans	Processed
2017	22,20884	102,409	0,85732	4,14792	0,4484	164,7624
2018	22,48239	102,7351	0,86038	4,17325	0,44885	165,9712
2019	22,76771	103,0562	0,86338	4,19404	0,44919	167,3458
2020	23,05956	103,3756	0,86636	4,21416	0,44948	168,7799
2021	23,35398	103,696	0,86934	4,23634	0,4498	170,1964
2022	23,65257	104,0164	0,87233	4,26	0,45011	171,6235
2023	23,95569	104,3368	0,87532	4,28543	0,45042	173,0654
2024	24,26298	104,6574	0,8783	4,31339	0,45074	174,5133
2025	24,5758	104,9776	0,88129	4,34385	0,45104	175,9883
2026	24,89306	105,2982	0,88427	4,37822	0,45135	177,4687
2027	25,22564	105,6122	0,88716	4,41191	0,45153	179,1363
2028	25,55369	105,9329	0,89015	4,45639	0,45183	180,6476
2029	25,87745	106,2604	0,89324	4,51284	0,45224	182,0102
2030	26,21614	106,5821	0,89625	4,57314	0,45255	183,54
2031	26,56171	106,9038	0,89925	4,64328	0,45284	185,0967
2032	26,91396	107,2257	0,90226	4,72535	0,45313	186,6717
2033	27,2729	107,5484	0,90528	4,82113	0,45343	188,2597
2034	27,6371	107,8729	0,90833	4,93237	0,45374	189,8327
2035	27,99857	108,2049	0,9115	5,06233	0,45415	191,2641
2036	28,41088	108,5099	0,91422	5,13978	0,45417	193,3599
2037	28,51202	109,0485	0,92074	5,53347	0,45684	190,6942
2038	28,47699	109,8065	0,93062	5,4959	0,46023	185,9636
2039	26,88186	115,3258	1,01525	5,76393	0,47278	153,7032
2040	27,26252	115,425	1,01525	6,36425	0,47263	156,0418

Table A8: Yearly production per species type for the 3 scenarios (in 000 tons/year)

Business as usual												
period	SASC	SARAS	SAOF	SAINT	SACAP	WFSC	WFCAP	OFCAP	MOCAP	MOINT	CRCAP	Proc
2017	1290.376	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1234.735
2018	1329.087	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1242.639
2019	1368.96	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1250.658
2020	1410.028	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1258.743
2021	1452.329	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1266.894
2022	1495.899	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1275.11
2023	1540.776	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1283.394
2024	1586.999	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1291.745
2025	1634.609	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1300.234
2026	1683.648	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1308.726
2027	1734.157	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1317.292
2028	1786.182	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1325.934
2029	1839.767	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1334.654
2030	1894.96	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1343.453
2031	1951.809	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1352.334

2032	2010.363	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1361.298
2033	2070.674	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1370.348
2034	2132.795	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1379.486
2035	2196.778	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1388.714
2036	2262.682	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1398.035
2037	2330.562	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1407.45
2038	2400.479	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1416.963
2039	2472.493	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1426.574
2040	2546.668	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1436.287
Scenario 1												
period	SASC	SARAS	SAOF	SAINT	SACAP	WFSC	WFCAP	OFCAP	MOCAP	MOINT	CRCAP	Proc
2017	1290.376	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1234.735
2018	1341.991	15.67	0.157	0.15	2.112	1.623	812.704	791.955	4.286	0.025	23.589	1244.034
2019	1395.67	18.804	0.188	0.173	2.112	1.623	812.704	791.955	4.286	0.028	23.589	1253.519
2020	1451.497	22.564	0.226	0.199	2.112	1.623	812.704	791.955	4.286	0.033	23.589	1263.222
2021	1509.557	27.077	0.271	0.228	2.112	1.623	812.704	791.955	4.286	0.038	23.589	1273.068
2022	1569.939	32.493	0.325	0.263	2.112	1.623	812.704	791.955	4.286	0.043	23.589	1283.063
2023	1632.737	38.991	0.39	0.302	2.112	1.623	812.704	791.955	4.286	0.05	23.589	1293.232
2024	1698.046	46.789	0.468	0.347	2.112	1.623	812.704	791.955	4.286	0.057	23.589	1303.907
2025	1765.968	56.147	0.561	0.399	2.112	1.623	812.704	791.955	4.286	0.066	23.589	1314.211
2026	1836.607	67.377	0.674	0.459	2.112	1.623	812.704	791.955	4.286	0.076	23.589	1324.998
2027	1910.071	80.852	0.809	0.528	2.112	1.623	812.704	791.955	4.286	0.087	23.589	1335.987
2028	1986.474	97.023	0.97	0.608	2.112	1.623	812.704	791.955	4.286	0.1	23.589	1347.244
2029	2065.933	116.427	1.164	0.699	2.112	1.623	812.704	791.955	4.286	0.115	23.589	1358.791
2030	2148.571	139.712	1.397	0.803	2.112	1.623	812.704	791.955	4.286	0.133	23.589	1370.664
2031	2234.513	167.655	1.677	0.924	2.112	1.623	812.704	791.955	4.286	0.152	23.589	1382.898
2032	2323.894	201.186	2.012	1.063	2.112	1.623	812.704	791.955	4.286	0.175	23.589	1395.537
2033	2416.85	241.423	2.414	1.222	2.112	1.623	812.704	791.955	4.286	0.202	23.589	1408.632
2034	2513.524	289.708	2.897	1.405	2.112	1.623	812.704	791.955	4.286	0.232	23.589	1422.24
2035	2614.065	347.649	3.476	1.616	2.112	1.623	812.704	791.955	4.286	0.267	23.589	1435.992
2036	2718.627	417.179	4.172	1.858	2.112	1.623	812.704	791.955	4.286	0.307	23.589	1451.855
2037	2827.372	500.615	5.006	2.137	2.112	1.623	812.704	791.955	4.286	0.353	23.589	1466.1
2038	2940.467	600.738	6.007	2.458	2.112	1.623	812.704	791.955	4.286	0.405	23.589	1484.254
2039	3058.086	720.886	7.209	2.826	2.112	1.623	812.704	791.955	4.286	0.466	23.589	1499.429
2040	3180.409	865.063	8.651	3.25	2.112	1.623	812.704	791.955	4.286	0.536	23.589	1520.84
Scenario 2												
period	SASC	SARAS	SAOF	SAINT	SACAP	WFSC	WFCAP	OFCAP	MOCAP	MOINT	CRCAP	Proc
2017	1290.376	13.058	0.131	0.131	2.112	1.623	812.704	791.955	4.286	0.022	23.589	1234.735
2018	1316.183	14.364	0.144	0.163	2.112	1.704	812.704	791.955	4.286	0.027	23.589	1241.562
2019	1342.507	15.8	0.158	0.204	2.112	1.789	812.704	791.955	4.286	0.034	23.589	1248.478
2020	1369.357	17.38	0.174	0.255	2.112	1.879	812.704	791.955	4.286	0.042	23.589	1255.457
2021	1396.744	19.118	0.191	0.319	2.112	1.973	812.704	791.955	4.286	0.053	23.589	1262.481
2022	1424.679	21.03	0.21	0.399	2.112	2.071	812.704	791.955	4.286	0.066	23.589	1269.562
2023	1453.173	23.133	0.231	0.498	2.112	2.175	812.704	791.955	4.286	0.082	23.589	1276.7
2024	1482.236	25.446	0.254	0.623	2.112	2.284	812.704	791.955	4.286	0.103	23.589	1283.898
2025	1511.881	27.991	0.28	0.778	2.112	2.398	812.704	791.955	4.286	0.128	23.589	1291.162

2026	1542.118	30.79	0.308	0.973	2.112	2.518	812.704	791.955	4.286	0.16	23.589	1298.491
2027	1572.961	33.869	0.339	1.216	2.112	2.644	812.704	791.955	4.286	0.201	23.589	1305.929
2028	1604.42	37.256	0.373	1.52	2.112	2.776	812.704	791.955	4.286	0.251	23.589	1313.402
2029	1636.508	40.982	0.41	1.9	2.112	2.915	812.704	791.955	4.286	0.313	23.589	1320.917
2030	1669.239	45.08	0.451	2.375	2.112	3.06	812.704	791.955	4.286	0.392	23.589	1328.547
2031	1702.623	49.588	0.496	2.969	2.112	3.213	812.704	791.955	4.286	0.49	23.589	1336.267
2032	1736.676	54.547	0.545	3.711	2.112	3.374	812.704	791.955	4.286	0.612	23.589	1344.08
2033	1771.409	60.001	0.6	4.639	2.112	3.543	812.704	791.955	4.286	0.765	23.589	1351.991
2034	1806.838	66.002	0.66	5.799	2.112	3.72	812.704	791.955	4.286	0.957	23.589	1360
2035	1842.974	72.602	0.726	7.249	2.112	3.906	812.704	791.955	4.286	1.196	23.589	1368.086
2036	1879.834	79.862	0.799	9.061	2.112	4.101	812.704	791.955	4.286	1.495	23.589	1376.436
2037	1917.431	87.848	0.878	11.326	2.112	4.306	812.704	791.955	4.286	1.868	23.589	1384.137
2038	1955.779	96.633	0.966	14.158	2.112	4.522	812.704	791.955	4.286	2.335	23.589	1393.099
2039	1994.895	106.296	1.063	17.697	2.112	4.748	812.704	791.955	4.286	2.919	23.589	1449.003
2040	2034.793	116.926	1.169	22.121	2.112	4.985	812.704	791.955	4.286	3.649	23.589	1454.376

A sensitivity analysis was conducted on parameters identified as the most uncertain and the results are summarized in Table A9. The model seems to be very sensitive to all parameters in NO-S2 but less in the other scenarios. This may be due to the increased production of other species than salmonids in this scenario that make the model unstable, which explains why their production could not be increased more than in NO-S2, even though the final quantities are much below the expected quantities of the industry.

Table A9: Results of the sensitivity analysis for Norway for a variation of +/-10% of the tested parameters, and analysis of the output in consumption, production, imports and exports quantities.

	NO-BAU	NO-S1	NO-S2
AIDS parameters +10%	Low	Medium	Low
AIDS parameters -10%	Low	Low	N.A.
Elasticities Demand +10%	Low	Low	N.A.
Elasticities Demand -10%	Low	Medium	N.A.
Elasticities Expenditure +10%	Low	Medium	N.A.
Elasticities Expenditure -10%	Low	High	N.A.
CES/CET +10%	Low	High	N.A.
CES/CET -10%	Low	Low	Low

“Low” means that the variation of all 4 outputs is lower than 2%, “Medium” means lower than 5% and “High” means that they are all higher than 5% (absolute value) (BAU= Business-as-usual; S1= Scenario 1; S2= Scenario 2; AIDS= Almost Ideal Demand System; CES/CET are the constant elasticities of substitution of imports and constant elasticities of transformations of exports; N.A.=Not Available because the model could not compute over the whole period of time).

1.6 CONCLUSION

In light of the results of this study, it seems that Norway would remain a major aquaculture producer and exporter in any of the scenarios. However, diversifying its production appears as a big challenge, and tackling it might require important financial investments to create more incentives in developing

other productions than salmons in sea cages (higher than modeled in this study) and/or technological breakthrough, which would make it easier to some technologies to emerge compared to sea cages salmons.

2 LIFE CYCLE ASSESSMENT APPLICATION

2.1 LIFE CYCLE IMPACT ASSESSMENT

Midpoint impact categories use indicators chosen along the cause-effect chain between emissions and damage to represent specific environmental effects. Endpoint indicators represent environmental effects at the end of the cause-effect chain also referred to as the damage level. Midpoint impact categories are expanded/linked to endpoint impact categories, which contribute to one of the two areas of protection (AoP) or endpoint indicators: Ecosystem quality and Human health. In the IMPACT World+ method, some endpoint impact categories are temporally differentiated (i.e. short term and long term).

Table A10: Impact categories assessed in this study, with their corresponding description.

	Impact category	Unit	Description
A	Climate change, short term ¹	kg CO ₂ eq (short term)	Effect of greenhouse gas accumulation in the atmosphere that leads to positive radiative forcing, which may cause different climate effects such as increasing temperature or extreme weather events. Based on Global Warming Potential for a 100-year time horizon
B	Climate change, long term ¹	kg CO ₂ eq (long term)	Effect of greenhouse gas accumulation in the atmosphere that leads to positive radiative forcing, which may cause different climate effects such as increasing temperature or extreme weather events. Based on Global Temperature Potential for a 100-year time horizon
M	Land occupation, biodiversity ¹	m ² arable land	Impacts on land due to anthropogenic occupation of land
N	Land transformation, biodiversity ¹	m ² arable land	Impacts on land due to anthropogenic transformation of land from its natural state
Q	Fossil and nuclear energy use ¹	MJ deprived	Primary energy content use from fossil fuels and nuclear sources
P	Mineral resources use ¹	kg deprived	Fraction of material needed by future users that are not able to adapt to a full dissipation of the easily available stock
O	Water scarcity ¹	m ³ world-eq	Remaining water available per area after human and aquatic ecosystem demand has been met, relative to the world average
C	Freshwater acidification ¹	kg SO ₂ eq	Negative effects of increasing acidification of the freshwater that may change the pH of the compartment and impact biodiversity
F	Terrestrial acidification ¹	kg SO ₂ eq	Negative effects of increasing acidification of the soil that may change the pH of the compartment and impact biodiversity
D	Freshwater eutrophication ¹	kg PO ₄ P-lim eq	Negative effect of increasing nutrient concentration in the freshwater that may lead to decreased levels of oxygen and therefore impact biodiversity
E	Marine eutrophication ¹	kg N N-lim eq	Negative effect of increasing nutrient concentration in the ocean that may lead to decreased levels of oxygen and therefore impact biodiversity
J	Freshwater ecotoxicity ¹	CTUe	Negative effect of chemical substances emitted in freshwater on local biodiversity
I	Particulate matter formation ¹	kg PM _{2.5} eq	Negative effect on human health due to inhalation of fine particulate matter (PM _{2.5}), i.e. particles with diameter less than 2.5 µm

H	Photochemical oxidant formation¹	kg NMVOC eq	Negative effect of increasing ozone concentration in the atmosphere which can lead to increased frequency and severity of respiratory diseases
K	Human toxicity cancer¹	CTUh	Negative effect of chemical substances emitted in freshwater, terrestrial and marine ecosystems, which might impact human population through different pathways (e.g. inhalation of air, ingestion of food and water), and may cause cancers
L	Human toxicity non cancer¹	CTUh	Negative effect of chemical substances emitted in freshwater, terrestrial and marine ecosystems, which might impact human population through different pathways (e.g. inhalation of air, ingestion of food and water), and may cause multiple diseases non-cancerous
G	Ionizing radiations¹	Bq C-14 eq	Negative effect due to release of radioactive material to the environment
S	Ozone Layer Depletion¹	kg CFC-11 eq	Negative effect due to the destruction of the ozone layer from human activity
R	NPPU²	kg C	Biotic resource that is not available for other systems anymore
U	Human health¹	DALY	Damages on the intrinsic value of human health, accounting for both mortality and morbidity
T	Ecosystems¹	PDF.m ² .yr	Damages on the intrinsic value of natural ecosystems, through potentially disappeared fraction of species

¹:(Bulle et al., 2019); ²:(Papatryphon et al., 2004)

2.2 DATA SOURCES AND ASSUMPTIONS

Table A11: References and hypothesis used to build the life cycle inventories.

Process	Source	Main hypothesis
Mealworm larvae production	Thevenot et al. (2018)	
Algal oil production	(Passell et al., 2013)	System expansion for the co-products (oil cakes and low value lipids)
Soybean meal	Based on Ecoinvent process	Gross energy allocation
Soybean oil		
Maize starch	Based on Ecoinvent process	
Wheat flour		
Wheat bran	Based on Agri-footprint process	Gross energy allocation
Wheat middling		
Wheat gluten		
Rice bran	Based on Agri-footprint process	Gross energy allocation with white rice, rice husks and rice broken
Rape oil	Based on Ecoinvent process	Gross energy allocation with rapeseed meal
Sunflower meal	Based on Agri-footprint process	Gross energy allocation with sunflower oil
Landed fish for fishmeal and fish oil	Based on Ecoinvent process (Landed anchovy)	
Fishmeal	Based on Ecoinvent process (Fishmeal, 65-67% protein, from anchovy)	Gross energy allocation
Fish oil		
Feed pellets production	(Samuel-Fitwi et al., 2013)	
Feed for freshwater fishes in RAS	(Rana et al., 2009)	

Fingerlings production	(Medeiros et al., 2017)	
Smolt production	(Colt et al., 2008)	
Floating platforms	(Baliao et al., 2000)	Extrapolated based on active surface
Marines cages	(Ayer et al., 2016)	
RAS O₃ for disinfection	(Xu et al., 2002)	
RAS production	(Liu et al., 2016)	
Offshore aquaculture	(García García et al., 2016)	
Mollusks production	(Lourguioui et al., 2017)	
Production in sea cages	(Liu et al., 2016)	
Enhance production of IMTA	(Reid et al., 2008)	
Ratio salmon/mussels production	(Whitmarsh et al., 2006)	
Boat consumption and emissions	https://www.oxe-diesel.com/About-Oxe/Emissions/CO2de	
Diesel generator consumption and emissions	(De Oliveira et al., 2015)	
Calculation of N and P emissions from production	(Papatriphon et al., 2005)	
Mussels nutrients needs and emissions during grow-out	(Brigolin et al., 2009)	
Net primary production use	(Papatriphon et al., 2004) (Pauly and Christensen, 1995)	
Edible yield of marine fishes	http://www.fao.org/3/T0219E/T0219E01.htm	
Edible yield of freshwater fishes (expected to be mainly Tilapia and Catfish)	(Jankowska et al., 2007) and (Garduño-Lugo et al., 2003)	
Edible yield of crustaceans (expected to be mainly crabs)	(US.FOODS, 2018)	
Edible yields of mussels	(Rivonker et al., 1993)	
Gutting and fileting	(Winther et al., 2009)	

List of main assumptions for Singapore:

Feed

- All marine ingredients are produced in Vietnam (closer important producer).
- All other ingredients (mainly cereals, but also insect-based meal and algal oil) are produced in China (closer important producer).
- All feed pellets are produced in Vietnam (closer important producer).
- Transport of feed from Vietnam is 1500 km by sea and 200 km by road.
- Feed composition for marine fishes produced for future technologies is similar to the one used for marine fishes produced in “high-tech” system.

Fingerlings

- All fingerlings originate from Malaysia.
- Fingerlings are transported by ships from Malaysia over 200 km.
- Weight of fingerlings when arriving to the farm is 1 g.

Production

- General
 - Occupational time of all farms is 50 years.

- For each category, equal weight is attributed to all farms visited because it is assumed that they are all equally representative.
- RAS clean the water "perfectly" and there is not waste in the discharged water.
- In all RAS, the wastewater is equal to half the input water (because of evaporation).
- In closed systems, 80% of the nutrients produced can be used as fertilizer.
- Marine fishes in "low-tech", or marine nets
 - For the fingerling growth step, only infrastructures and feed are considered because of lack of information on the rest.
 - Half of the surface on-land is covered by building.
 - There are 50% more nets than pools.
 - Weight of a 20 L plastic container is 1 kg.
 - Thickness of the rearing tanks is 3 cm.
 - Width of the wooden floor is 10 cm.
 - Lifetime of marine nets is 5 years.
 - Lifetime of other infrastructures is 20 years.
 - Average weight of fish produced is 700 g.
- Marine fishes in "high-tech" systems, or marine cages
 - Half of the surface on-land is covered by building.
 - Lifetime of nets is 5 years.
 - Lifetime of RAS system is 10 years.
 - Lifetime of the rearing tanks is 20 years.
 - Thickness of the rearing tanks is 3 cm, diameter is 3 m, depth is 1.2 m and amount is 20 pieces.
 - RAS is constituted by 1000 m of pipes, 500 kg of plastic and 100 kg of concrete.
 - Average weight of fish produced is 4.5 kg.
- Freshwater fishes in "low-tech" systems, or concrete ponds
 - Motors used to make the water circulate are neglected.
 - Lifetime of the ponds is 20 years.
 - Thickness of concrete for the ponds is 30 cm.
 - Depth of the ponds is 2 m.
 - Average length of water pipes bringing water to a pond is 130 m, and there is an average of 4 pipes per pond.
 - Average weight of fish produced is 500 g.
- Marine fishes in RAS
 - All surface on land is covered by buildings.
 - Average weight of fish produced is 700 g.
- Marine in offshore systems
 - Half of the surface on-land is covered by building.
 - FCR in 2017 is equal to the one of marine fishes in "high-tech", but uneaten feed proportion is higher (20%).
 - Average weight of fish produced is 4.5 kg.
- Freshwater fishes in RAS
 - All surface on land is covered by buildings.
 - Average weight of fish produced is 500 g.
- Crustaceans in "high-tech" systems
 - A quarter of the on land area is covered by building.
 - Lifetime of the boxes is 5 years.
 - Lifetime of the RAS is 10 years.
 - Recirculation rate of the RAS is 4 times a day.
 - Boxes are 2 cm thick with a permanent 5 cm water in it.
 - The RAS has 500 m of pipes, 100 kg of plastic and 10 kg of steel.
- Mollusks in "low-tech" systems
 - The nutrients cycle is similar to blue mussels on Baltic Sea.
 - All the on land area is covered by a constructed hall.
 - A quarter of the area at sea is covered with the wooden platform.

- The platform has the same characteristics than the one for marine fishes in “low-tech”
- Mussels’ larvae are handpicked in Singapore and are therefore not imported from Malaysia.

List of main assumptions for Norway:

Feed

- All marine ingredients are produced in Norway (important producer) and the mix of fish species for FMFO are taken as an average between Ewos, Skretting and Biomar (three biggest FMFO producers in Norway)
- Insect-based meal and algal oil are produced in Norway.
- All other ingredients are produced in France (closer important producer) except soybean that is produced in Brazil (global main producer).
- All feed pellets are produced in Norway.

Fingerlings

- All fingerlings originate from Norway, and are transported 200 km in average.
- Weight of fingerlings when arriving to the farm is 1 g.
- Weight of a smolt when arriving to the farm is 87,5g.

Production

- General
 - Occupational time of all farms is 50 years.
 - RAS clean the water "perfectly" and there is not waste in the discharged water.
 - In all RAS, the wastewater is equal to half the input water (because of evaporation).
 - In closed systems, 80% of the nutrients produced can be used as fertilizer.
- Salmons in sea cages
 - Average weight of fish produced is 4.6 kg.
- Salmons in RAS
 - All surface on land is covered by buildings.
 - Average weight of fish produced is 4.6 kg.
- White fishes in sea cages
 - Average weight of fish produced is 3kg.
 - Juvenile growth based on smolt: even if the growth time of a juveniles white fish is shorter than a smolt, same inventory per kg because less optimized system.
 - The white fishes reach commercial size after 21 months in the sea cages so 1.8 times more than salmon therefore the need in infrastructures is 1.8 times more. (<https://thefishsite.com/articles/cultured-aquatic-species-atlantic-cod>).
 - The white fish have a lower density than salmon, therefore the infrastructures needed are 2.5 times more.
 - Juveniles farming is based on MFHT.
- Salmons and mollusks in IMTA
 - The nutrients cycle is similar to blue mussels on Baltic Sea.
 - All the on land area is covered by a constructed hall.
 - The proportion of mussels produced linked to 1 site of salmon is always the same (this is because it is not unlimited, and with the Whitmarsh proportion 1:6.5 arounds 30% of the nutrients emissions of the salmons are used by the mussels, which seems possible).
 - Boats requirements of the mussels are covered by the boat requirements of the salmons.
 - There is an enhance production of the mussels because IMTA of 50% (based on Reid (2008)) meaning that the mussels are growing 50% faster. It does not affect the cleaning.

Table A12: Technology maturity and corresponding decrease of water and energy consumption between 2017 and 2040

Category	Degree of maturity	Decrease in input within 2017-2040
MFLT	Mature	5%
MFHT	Improving	10%
MFOF	New	15%
MFRAS	New	15%
FFLT	Aging	0%
FFRAS	New	15%
CRHT	Improving	10%
MOLT	Aging	0%
SASC	Aging	0%
SARAS	New	15%
SAOF	New	15%
SAINT	Aging	0%
MOINT	Aging	0%
WFSC	Very new	20%

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