GLOBAL SEAFOOD PRODUCTION FROM MARICULTURE: CURRENT STATUS, TRENDS AND ITS FUTURE UNDER CLIMATE CHANGE

by

Muhammed Alolade Oyinlola

B. AQFM., University of Agriculture, Abeokuta, Nigeria, 2010
M.Sc., Universität Bremen, Germany, 2014

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

The Faculty of Graduate and Postdoctoral Studies
(Zoology)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

October 2019

© Muhammed Alolade Oyinlola, 2019
The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the dissertation entitled:

Global seafood production from mariculture: current status, trends and its future under climate change

submitted by Muhammed Alolade Oyinlola in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Zoology

Examing Committee:
Dr. William Wai Lung Cheung
Supervisor
Dr. Daniel Pauly
Supervisory Committee Member
Dr. Evgeny Pakhomov
University Examiner
Dr. Xiaonan Lu
University Examiner

Additional Supervisory Committee Members:
Dr. Rashid Sumaila
Supervisory Committee Member
Dr. Max Troell
Supervisory Committee Member
Abstract

Mariculture is growing rapidly over the last three decades at an average rate of about 3.7% per year from 2001 to 2010. However, questions about mariculture sustainable development are uncertain because of diverse environmental challenges and concerns that the sector faces. Changing ocean conditions such as temperature, acidity, oxygen level and primary production can affect mariculture production, directly and indirectly, particularly the open and semi-open ocean farming operations.

This dissertation aims to understand climate change impact on future seafood production from mariculture. Firstly, I update the existing Global Mariculture Database (GMD) with recent mariculture production and create a farm-gate price database to match the production data. I show that global mariculture production in 2015 was 27.6 million tonnes, with a farm-gate value of USD 85 billion. Secondly, I develop quantitative models to predict the present-day global suitable marine area for mariculture. The results show that total suitable mariculture area for the 102 farmed species is 72 million km²: 66 million km², 39 million km² and 31 million km² for finfish, crustaceans and mollusc respectively. Thirdly, I predict climate change impact on suitable marine areas and diversity. Results show that climate change may lead to a substantial redistribution of mariculture species richness, with large decline in potential farm species richness in the tropical to sub-tropical regions. Fourthly, I predict global mariculture production potential (MPP) under climate change. Results suggest that global mariculture production potential will decrease substantially by 16% in the 2050s relative to 2020s under the business as usual scenario. Finally, I develop a set of shared socioeconomic pathways for mariculture to assess the plausible future scenarios for sustainable mariculture under global change. The results highlight that future
mariculture development and sustainability will depend on the efficiency of four domains; science and technology; society; governance and economics.

Overall, the dissertation shows that climate change is a major threat to seafood production from mariculture. Climate change effect will depend on the species that are farmed, their locations and the farming operation/technology employed. Future research on the sustainable development pathway for mariculture should further expand on socio-economic modelling and projections.
Lay summary
Most world fish stocks are already fully- or over-exploited, and their potential catches are projected to decrease under climate change. Mariculture has been suggested as a panacea for sustainable seafood production. However, climate change can impact marine farming systems. This dissertation aims to understand mariculture potential contribution to seafood production under climate change. I update mariculture production database and create farm-gate price database. Results show that mariculture continues to grow globally at 4.4% per year (2011-2015). Using modelling tools, I estimated that the global area suitable for mariculture amounts to 72 million km². Moreover, mariculture species diversity is projected to decline by 10 to 40%, particularly in tropical and sub-tropical regions. Also, future mariculture risks and vulnerabilities will be exacerbated if the world becomes regionalised towards trades and markets, with low environmental awareness and concerns. Overall, these findings suggest that sustainable seafood production from mariculture is uncertain under climate change.
Preface

I am the senior author in all chapters. I took primary responsibility for the research contained in the chapters, including the design, data collection, analysis and writing. Dr William Cheung, Dr Rashid Sumaila, Dr Daniel Pauly, and Dr Max Troell contributed their expertise and advice with ideas, methods and data interpretation. All chapters of this dissertation have been published, submitted for publication or being prepared for submission.

Part of Chapter 1, 3 and appendix A has been published as a book chapter. The reference is cited as follows:


Chapter 3 has been published in a peer-reviewed journal. The reference is cited as follows:


I designed, performed and wrote the first draft of the study. Gabriel Reygondeau and William Cheung guided with data analysis of the data. Colette Wabnitz and Max Troell provided advice and guidance throughout the writing of the paper. Also, part of the chapter was published in a peer-reviewed paper I co-author.

Chapter 4 co-authors are William Cheung, Gabriel Reygondeau and Colette Wabnitz. This chapter has been submitted for publication in a peer-reviewed journal.


Chapter 5 is being prepared for publication. I developed the methods, collected the data, performed analysis and wrote the manuscript. Cheung, W. and Reygondeau, G. helped with modelling tools. Cashion, T. provided fishmeal and fish oil data. Campbell B. and D. Pauly contributed with guidance on mariculture database, U.R. Sumaila contributed with guidance on farm-gate price database. Max Troell contributed with guidance on aquaculture technicalities. All co-authors contributed to the final version.

Chapter 6 has been prepared for submission to a peer-review journal:


I developed the methods and wrote the draft of the manuscript. All co-authors took part in the analysis. This research is approved by the University of British Columbia Behavioral Research Ethics Board (UBC BREB NUMBER: H17-02016)
# Table of contents

Abstract ........................................................................................................................................ iii

Lay summary .................................................................................................................................. v

Preface ........................................................................................................................................... vi

Table of contents ............................................................................................................................. viii

List of tables ................................................................................................................................. xiii

List of figures ................................................................................................................................. xv

Acknowledgements ...................................................................................................................... xx

Dedication ....................................................................................................................................... xxi

Chapter 1 ......................................................................................................................................... 1

1.1 Introduction ............................................................................................................................... 1

1.2 Challenges of mariculture development .................................................................................... 3

1.3 Mariculture under climate change ........................................................................................... 5

1.4 Research objectives .................................................................................................................. 7

Chapter 2: Past and current status of global mariculture production: an update ......................... 11

2.1 Introduction ............................................................................................................................... 11

2.2 Methodology and data collection ............................................................................................ 13

2.3 Results ....................................................................................................................................... 14

2.3.1 Current trends in global mariculture ..................................................................................... 14

2.3.2 Global farm-gate price trends ................................................................................................. 24
4.2 Materials and methods ........................................................................................................... 59

4.2.1 Occurrence data ................................................................................................................ 60

4.2.2 Environmental data .......................................................................................................... 61

4.2.3 Habitat suitability index .................................................................................................... 61

4.2.4 Present suitable areas for mariculture ............................................................................... 62

4.2.5 Model testing ..................................................................................................................... 63

4.2.6 Projection of future suitability index ................................................................................. 64

4.2.7 Analysis ............................................................................................................................. 64

4.3 Results .................................................................................................................................. 65

4.3.1 Model evaluation ............................................................................................................... 65

4.3.2 Current mariculture richness and potential suitable marine area for mariculture... 66

4.3.3 Climate change induced impacts on mariculture richness and suitable mariculture area ........................................................................................................................................ 69

4.3.4 Projected climate change impacts on the exclusive economic zones (EEZs) with existing mariculture industry ........................................................................................................ 76

4.3.5 Impact of climate change on important mariculture species ......................................... 80

4.4 Discussion ............................................................................................................................. 83

Chapter 5. Projecting future seafood production from mariculture under climate change........ 88

5.1 Introduction .......................................................................................................................... 88

5.2 Methodology ......................................................................................................................... 90
5.2.1 Mariculture production and their direct and indirect drivers .................................................. 90
5.2.2 Model structure and development .......................................................................................... 92
5.2.3 Model evaluation ................................................................................................................. 100
5.3 Results .................................................................................................................................. 100
5.3.1 Estimated decline in fishmeal and fish oil production under climate change ...... 100
5.3.2 GAM model evaluation ........................................................................................................ 104
5.3.3 Future changes in mariculture production potential (MPP) in the 21st century .... 105
5.4 Discussion ............................................................................................................................... 113
5.4.1 Future seafood production from mariculture ................................................................. 113
5.4.2 Current mariculture development and their sensitivity to climate change impact. 115
5.4.3 Model structure .................................................................................................................. 116
5.4.4 Limitations of the study ....................................................................................................... 117
5.5 Conclusion .............................................................................................................................. 118

Chapter 6: Scenarios for mariculture development in the twenty-first century using shared socioeconomic pathways .............................................................................................................. 119
6.1 Introduction .............................................................................................................................. 119
6.2 Methodology ........................................................................................................................... 124
6.2.1 Storyline description for mariculture shared socioeconomic pathways (SSPMs).... 127
6.2.2 Data analysis ...................................................................................................................... 128
6.3 Results .................................................................................................................................. 128
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3.1</td>
<td>Key findings from the survey</td>
<td>128</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Review of main opportunities and concerns for mariculture development based on participant discussion</td>
<td>130</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Organising opportunities and concerns into domains and identifying drivers</td>
<td>131</td>
</tr>
<tr>
<td>6.4</td>
<td>SSP storylines for mariculture</td>
<td>135</td>
</tr>
<tr>
<td>6.5</td>
<td>Discussion</td>
<td>146</td>
</tr>
<tr>
<td>6.6</td>
<td>Conclusion</td>
<td>149</td>
</tr>
<tr>
<td>7.1</td>
<td>General conclusion</td>
<td>151</td>
</tr>
<tr>
<td>7.2</td>
<td>Limitations and uncertainties</td>
<td>156</td>
</tr>
<tr>
<td>7.3</td>
<td>Future directions</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>Appendices</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Appendix A</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Appendix B</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>Appendix C</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>Appendix D</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>Appendix E</td>
<td>219</td>
</tr>
</tbody>
</table>
List of tables

Table 2. 1. Average annual growth rate of mariculture production (%) in different regions. ...... 15

Table 2. 2. Annual mariculture production of the top 20 countries by total production. ........... 16

Table 2. 3. The main farmed species in production in the world from 2005 to 2015................... 20

Table 2. 4. The top five countries in mariculture production. .............................................. 22

Table 3. 1. Selected criteria for defining the potential area for mariculture production........... 38

Table 4. 1. Criteria for identifying marine area as suitable for mariculture production......... 63

Table 4. 2. Percentage change in global mariculture species richness by mid-century and end of the century relative to the 2005s under RCP 2.6 and 8.5 scenarios......................... 69

Table 4. 3. Percentage change in EEZs with currently established mariculture operations for select species by mid-century and end of the century relative to the 2005s under RCP 2.6 and 8.5 scenarios. ............................................................... 77

Table 5. 1. List of model variables and data source.............................................................. 99

Table 5. 2. Projected percentage change in global maximum catch potential (MCP) of forage fishes in the 2050s from the current period under RCP2.6 and RCP8.5 scenarios…100

Table 5. 3. Percentage change in projected fishmeal and fish oil production from the top 15 producing countries in the 2050s relative to the current period under RCP2.6 and RCP8.5......................................................... 102
Table 5. 4. GAM model developed for this study and the corresponding GCV scores............ 104

Table 5. 5. Percentage change in global mariculture production potential (MPP) by the mid century and the end of the 21st century relative to the 2010s under RCP 2.6 and 8.5 scenarios. ......................................................................................................................................................... 106

Table 5. 6. Percentage change in the currently farmed finfish and mollusc species mariculture production potential by mid-century relative to the 2010s under RCP 2.6 and 8.5 scenarios. ........................................................................................................................................................................... 108

Table 6. 1. Summary of factors selected that contribute to the expansion and further development of mariculture initiatives.................................................................125

Table 6. 2. Factor analysis identifying the main drivers of future mariculture development as identified by the survey. ............................................................................................................. 130

Table 6. 3. Summary of assumptions for each Shared Socioeconomic Pathways for Mariculture. .............................................................................................................................................................................. 145
List of figures

Figure 1. 1. Global trends in food fish production from 1950 to 2010 with production from capture fisheries, freshwater aquaculture and mariculture. ................................................................. 2

Figure 1. 2. A conceptual framework illustrating the direct and indirect impacts of climate change on mariculture. ................................................................. 7

Figure 1. 3. Schematic diagram illustrating the structure of this dissertation and linkages between core chapters. ................................................................. 8

Figure 2. 1. Global mariculture production from 1950 to 2015 ................................................................. 15

Figure 2. 2. Mariculture production (a) and value (b) by region from 1950 - 2015. .................... 17

Figure 2. 3. The temporal change in the annual growth rate of mariculture in the different regions and the world. ................................................................. 19

Figure 2. 4. Time-series of mariculture production of finfish and crustaceans and molluscs from 1950 to 2015. ................................................................. 21

Figure 2. 5. Temporal change in the mean trophic level of mariculture production in the different region and the world, 1950-2015 ................................................................. 23

Figure 2. 6. Global average mariculture farm-gate price by species group: crustaceans (red), molluscs and finfish. (a) Farm-gate price per tonnes (b) Total farm-gate value. ...... 25

Figure 2. 7. The proportion of farm-gate value contributed by each world region. ................... 26
Figure 3. 1. Geo-referenced world mariculture locations for all farmed species in the model. ... 33

Figure 3. 2. ENFA biplot with the x-axis (marginality) and y-axis (specialisation). .................. 35

Figure 3. 3. Prediction evaluation of each SDM used in the analysis. ................................. 40

Figure 3. 4. Relationship between predicted mariculture habitat suitability index (HSI) and natural occurrence habitat suitability index. ................................................................. 41

Figure 3. 5. Predicted suitable marine area for mariculture and the agreement among SDMs. .... 43

Figure 3. 6. Potential marine area suitable for mariculture production and current versus potential farmed species richness. ................................................................. 44

Figure 3. 7. Predicted marine area suitable for mariculture from four species distribution models. ................................................................. 45

Figure 3. 8. Latitudinal predicted species richness. ................................................................. 45

Figure 3. 9. Global predicted potential mariculture area and regional farmed species richness... 47

Figure 3. 10. Total predicted potential mariculture area for 20 of the most cultured species based on cumulative production from 1950 -2010.. ................................................................. 49

Figure 4. 1. Prediction evaluation of each SDM used in the analysis .................................. 65

Figure 4. 2. Predicted global distribution and range of mariculture species richness for the reference period (1995-2015) for 85 species of finfish and molluscs under RCP 8.5. ............ 67
Figure 4. 3. Regional predicted potential suitable mariculture area for 85 species for the present, 2050s and 2090s under RCP 2.6 and RCP 8.5 scenarios.......................................................... 68

Figure 4. 4. Impacts of climate change on global mariculture species richness for 85 of the currently most commonly farmed species by the 2050s relative to the 2005s under RCP 2.6 and RCP 8.5 scenarios................................................................. 70

Figure 4. 5. Impacts of climate change on global mariculture species richness for the 85 most common currently farmed species by the 2050s relative to the 2005s. ......................... 71

Figure 4. 6. Latitudinal average of the mean percentage change in mariculture species richness in the 2050s compared to the 2005s under RCP 2.6 and RCP 8.5 scenarios............... 73

Figure 4. 7. Regional predicted potential mariculture area for finfish for the present, 2050s and 2090s under RCP 2.6 and RCP 8.5 scenarios................................................................. 74

Figure 4. 8. Regional predicted potential mariculture area for molluscs for the present, 2050s and 2090s under RCP 2.6 and RCP 8.5 scenarios................................................................. 75

Figure 4. 9. Impacts of climate change on mariculture species richness for 85 of the currently most farmed species, limited to countries presently practising mariculture for selected species, by mid-century relative to 2005s under RCP 2.6 and RCP 8.5 scenarios.... 78

Figure 4. 10. Projected impact of climate change on finfish and mollusc mariculture species richness for the exclusive economic zones with present mariculture activities under RCP 2.6 and RCP 8.5 scenarios................................................................. 79
Figure 4. 11. Percentage changes in potential suitable mariculture area for countries currently farming selected species by the middle of the century relative to 2005s under RCP 2.6 and RCP 8.5 scenarios. .................................................................................................................. 81

Figure 4. 12. Impacts of climate change on global suitable marine areas for mariculture for currently farmed species by the 2050s relative to 2005s under RCP 2.6 and RCP 8.5 scenarios ........................................................................................................................................................................... 82

Figure 5. 1. Schematic representation of the structure of the model used to project mariculture production potential .................................................................................................................................................................. 94

Figure 5. 2. Historical and projected catch of forage fishes in the 21st century under RCP2.6 and RCP8.5 scenarios .................................................................................................................................................................. 101

Figure 5. 3. Percentage changes in fishmeal and fish oil production under RCP2. 6 and RCP8.5 scenarios. ............................................................................................................................................................................. 103

Figure 5. 4. Predicted mariculture production potential of 25% randomly selected data vs. average historical mariculture production ........................................................................................................................................... 105

Figure 5. 5. Percentage changes in mariculture production potential (MPP) for the current 85 most farmed species by mid-century relative to present under RCP 2.6 and RCP 8.5 scenarios. ......................................................................................................................................................... 107

Figure 5. 6. Percentage change in the currently farmed finfish mariculture production potential by the mid-21st century relative to the 2010s under RCP 2.6 and RCP8.5 scenarios... 109
Figure 5. 7. Percentage change in the currently farmed mariculture production for molluscs potential by the 2050s relative to the 2010s under RCP2.6 and RCP8.5 scenarios. 110

Figure 5. 8. Percentage changes in mariculture production potential (MPP) for the current 85 most farmed species by mid-century relative to 2020 under RCP 2.6 and RCP 8.5 scenarios. 112

Figure 6. 1. The Shared Socioeconomic Pathways framework.................................123

Figure 6. 2. Main social and ecological concerns identified from the survey that contribute to the main issues associated with future mariculture development.......................... 129

Figure 6. 3. A schematic diagram illustrating the relative contributions of each domain to mariculture sustainability within SSPMs......................................................... 144
Acknowledgements

I wish to appreciate my supervisor; Dr William Cheung, for his close supervision and directions at all stages my PhD. You are such a kind and wonderful person. My profound gratitude to supervisory members; Dr Rashid Sumaila, Dr Daniel Pauly, and Dr Max Troell, for their advice and inspiration. I thank the faculty, staff and students of the Institute for the Oceans and Fisheries for their support throughout my PhD sojourn. Special thanks to Dr Yoshitaka Ota, Dr Colette Wabnitz, Dr Gabriel Reygondeau, Dr Vicky Lam, Dr Wilf Swartz, Dr Andrés Cisneros-Montemayor, Dr Oai Li Chen, Ms Elina Hsieh and all Nereus program fellows for their assistance, stimulating discussion and beneficial information. I am thankful for my colleagues and friends in Changing Ocean Research Unit (CORU), Ravi Maharaj, Tayler Clarke, Juliano Palacious Abrantes, Patricia Angkiriwang, Travis Tai, Virginie Bornarel for your friendship and support. This dissertation would not have been possible and completed without the funding from the Nippon Foundation through the Nereus Program and the University of British Columbia Graduate Fellowship.

A billion thanks to my wife Mariam Oyinlola, the real pillar of tranquillity, care, love and personal cheerleader for your daily inspiration and supports. I am most grateful to my family, Alhaji and Alhaja A.G Oyinlola; Engr. Ismail and Suliah Adeniji, Dr Idris and Ganiyah Aiyeloja, Alhaji Nafiu and Jarinat Bamiji, and Nafisah Oyinlola for their encouragement and prayers at all stages of life.
Dedication

To every African child with a dream
Chapter 1

1.1 Introduction

World population will reach an estimated 9-10 billion people by 2050, increasing global food demand (McMichael, 2007; Silva and Soto, 2009; Godfray et al., 2010; Ray et al., 2012). Meeting the fundamental food requirement for everyone in the world is a crucial challenge to sustainable development (UN, 2013). Some studies point out that the world will need 70 to 100% more food by 2050 (Baulcombe et al., 2009; Alexandratos, 2012). However, the ability to meet food demand for the increasing population will depend on the efficiency of food production systems, the sustainability of production methods, and the equality in the distribution of food across the world’s populations (Silva and Soto, 2009).

Aquaculture (See appendix A for detailed definition and types) has played a significant role in filling the gap between the demand and supply of fish, with both freshwater and marine aquaculture (including brackish environments) providing nearly 80 million tonnes of food fish\(^1\) for consumption worldwide in 2016 (FAO, 2018) (Figure 1.1). The global production of fish from aquaculture has increased from 1970 to 2016, from 3 to 80 million tonnes (FAO, 2018). From 2011 to 2016, the average annual rate of increase of aquaculture production is estimated to be 6%, down from an average of 9% between 1980 and 2010 (FAO, 2012). Aquaculture is considered to be the fastest-growing agro-food sector in the world (Toufique and Belton, 2014).

In 2016, approximately 29 million tonnes (36%) of the total production from aquaculture originated from marine and brackish environment (i.e., mariculture) (FAO, 2018). Mariculture takes place in seawater, such as fjords, inshore and open waters, and inland seas or inland facility

\(^1\)“Fish” here includes finfish and aquatic invertebrates, but exclude aquatic plants
Recirculating Aquaculture System, RAS) in which the salinity generally exceeds 20 Practical Salinity Unit (PSU) (FAO, 2002). More than 60% of this production was from the farming of molluscs and crustaceans. Mariculture production has expanded by 9.3% in production since 1990 (Campbell and Pauly, 2013; FAO, 2014). Currently, 112 countries and territories produce seafood in the marine environment (Campbell and Pauly, 2013) with revenues reaching 67.4 billion USD in 2016 from the mariculture sector (FAO, 2018). Such revenues represented 29.1% of the total aquaculture income. Given the significant contribution of mariculture to seafood supply and the economy, various attempts are being made to estimate the potential to expand this sector (Gentry et al., 2017). Specifically, to understand the potential for further mariculture development and to facilitate the planning of ocean-based activities, there are demands for information on area potentially suitable for mariculture at present and in the future (Edgar et al., 2014; Venter et al., 2014).

Figure 1. 1. Global trends in food fish production from 1950 to 2010 with production from capture fisheries, freshwater aquaculture and mariculture. Data from Sea Around Us (2010) and FAO (2012).
1.2 Challenges of mariculture development

The contribution of mariculture to global aquaculture production has increased markedly from 14% in 2000 to 35.9% in 2016 (FAO, 2018). The Sea Around Us global mariculture database (www.searoundus.org) estimated the production of 5 million tonnes in 1990; which increased to 21 million tonnes by the end of 2010. This increase has been attributed to the growing demand for seafood (marine and brackish waters) in developed countries (Campbell and Pauly, 2013; FAO, 2014), which focuses on high value omnivorous, carnivorous finfish and crustacean species and marine bivalves (FAO, 2014). However, mariculture is suggested to have potential to contribute to solving food security challenges (Tacon, 2001; Ahmed and Lorica, 2002; Liu et al., 2018) and support employment and livelihood opportunities especially in developing regions with the high suitable marine area for mariculture (Subasinghe et al., 2009). Currently, there are over 112 countries and territories in which mariculture contributes to their gross domestic product (GDP) (Campbell, 2011) and more than half of these are developing countries.

Despite the interest in expanding mariculture to increase seafood production, concerns about its environmental impact (Naylor et al., 2000) and the availability of suitable space (Hofherr et al., 2015) are also growing. For example organic farm waste from mariculture activities (Buschmann et al., 2009) can lead to sediment organic enrichment and eutrophication (Mirto et al., 2010; Li et al., 2013), and subsequently changes the physicochemical properties and micro-flora biodiversity of benthic sediments in and around mariculture areas (Buschmann et al., 2009; Mirto et al., 2010). Also, fishmeal and fish oil (FMFO) are essential components of aquafeed, particularly for omnivorous and carnivores farmed species, which are mainly from small pelagic forage fishes (Metian and Tacon, 2009). Thus, the demand for fishmeal and oil may exert pressure
on wild fish stocks. Although fishmeal and fish oil as feed ingredient can be restricted for use in higher value starter (fry), finisher and broodstock feed only (Tacon and Metian, 2008) the demand for nutrients from capture fisheries from a rapidly growing mariculture is still a concern. Efforts have been made for more than a decade to find a replacement for fishmeal and oil using plant-based sources (Gómez-Requeni et al., 2004b; Harley et al., 2006; Patil et al., 2006; Klinger and Naylor, 2012). Other potential environmental concerns from mariculture include pollutions derived from the application of pharmaceuticals, antibiotics, and heavy metal contamination (Buschmann et al., 2009; Li et al., 2013), the introduction of alien species, genetic interactions, disease transfer (Grigorakis and Rigos, 2011) and the destruction of coastal habitats such as mangroves (Rimmer et al., 2013).

Climate change and ocean acidification will also affect the future development of mariculture. Most mariculture activities take place mainly in sheltered areas of the coastal zone, which include habitats such as estuaries, salt marshes, mudflats and more recently in the open ocean. The adverse effects of climate change such as increases in water temperature and, ocean acidity, changes in salinity, storm frequencies, wave action and sea-level rise, among others - are expected to impact the suitability of marine habitats (open sea and coastal waters) for farming seafood (Harley et al., 2006; Barange and Perry, 2009; Cheung et al., 2009; Gattuso et al., 2015; Barange et al., 2018). These impacts may affect the quantity and quality of seafood production from mariculture.
1.3 Mariculture under climate change

The ocean ecosystems are observed to respond to climate change in different ways; these include increase in temperature, sea-level rise, salinity shift, ocean acidification, reduced or increased productivity (Chlorophyll a), wave action and other effects of the weather and climate patterns (Pörtner et al., 2014). The global oceans absorbed about 93% of the extra heat as a result of greenhouse gas emissions from human activities (Pörtner et al., 2014). As a result, the global seawater temperature has increased in the last century (IPCC, 2014). Also, change in the sea level is linked to thermal expansion of seawater and increasing melting glaciers and ice sheets (Aschwanden et al., 2019). The rate of global mean sea-level rise has increased since the early 20th century, with estimates that range from zero mm to 0.013 mm year\(^2\) (Church et al., 2013). Sea level is projected to rise 10 cm to 100 cm over this century in which thermal expansion will contribute 10 to 43 cm and melting glaciers contributing 23 cm (Church et al., 2013). The ocean has absorbed almost 30% of CO\(_2\) emitted from human activities (Pörtner et al., 2014). The uptake of anthropogenic CO\(_2\) from the atmosphere by the ocean decreases the seawater pH (IPCC, 2014). The effect of increased pCO\(_2\) reduces calcium carbonate (CaCO\(_3\)) saturation, which affects the shell formation of shellfish (Gazeau et al., 2010; Clements and Chopin, 2016).

Climate change is expected to impact mariculture (Silva and Soto, 2009; Barange et al., 2018), although, the extent, types, and distribution of impacts have not been well understood (Figure 1.2). Most mariculture organisms are ectotherms that are farmed in open or semi-open facilities (Appendix A). Their metabolism and physiological functions are sensitive to changing environmental temperature (Williams and Rota, 2010). Thus, environment conditions directly affect their growth rate and reproduction, while species’ environmental preference and tolerances
also restrict the area where particular species are farmed (Kapetsky et al., 2013a). Consequently, changes in environmental conditions under climate change affect the suitability of the environment for farming different species (Barange et al., 2018; Froehlich et al., 2018). Also, ocean acidification can impact the growth and survival of shellfish, particularly in the early life stages (Gazeau et al., 2010; Kroeker et al., 2013). For example, in the west coast of the United States, the decrease in pH from increased in the intensity of coastal upwelling led to large mortalities of oyster larvae in the hatchery facilities, leading to substantial economic losses (Barton et al., 2012; Barton et al., 2015).

Other elements of climate change such as sea-level rise, saltwater intrusion, and ocean productivity will also affect the suitability of coastal and ocean areas for mariculture through the destruction of infrastructure with sea-level rise, disease prevalence because of saltwater intrusion (Joffre et al., 2010) and reduced growth for shellfish with decline ocean productivity (Naylor et al., 2000). Climate change will also affect mariculture indirectly through its impacts on wild capture fisheries. Most finfish mariculture is currently dependent on wild capture fisheries for supplies of fishmeal and fish oil, and in some cases, fish fries or juveniles for grow-out operations (Tacon et al., 2011). Climate change is projected to lead to decrease in biomass and maximum catch potential of marine fish stocks and fisheries (Cheung et al., 2010), which may indirectly impact mariculture operations (Figure 1.2).
1.4 Research objectives

The overall goal of this doctoral research is to understand the potential of future seafood production from mariculture in the world under climate change. Specifically, the dissertation considers biological, environmental, social and economic factors in determining the future of mariculture production. This dissertation is structured into seven chapters, with chapter 1 and 7 being the general introduction and conclusion of the dissertation, respectively (Figure 1.3).
Figure 1. 3. Schematic diagram illustrating the structure of this dissertation and linkages between core chapters.

An important step towards understanding the sustainability of global mariculture development is to have reliable and comprehensive mariculture data. Such databases support the analysis of status and trends of mariculture development and facilitate the development of scenarios and models to project the future of mariculture. The Global mariculture Database (GMD) of the Sea Around Us (www.searoundus.org) is the most comprehensive global mariculture (including brackish aquaculture) data divided by taxa by each province or state for each maritime country that engages in mariculture. Currently, the GMD provides mariculture data from 1950 to
2010 and also lacking a corresponding farm price data. Therefore, in chapter 2, I aim to update the Global Mariculture Database (GMD) and create a new farm-gate price database. This chapter provided the mariculture production data, farm-gate price and mariculture countries information that was used in chapter 3 to 6 of this dissertation.

The objective of chapter 3 is to predict the areas of the world ocean that are suitable for mariculture. The rationale of this chapter is to develop a site selection model tool for identifying marine areas that offer suitable environmental conditions for currently farmed species. Specifically, species distribution models (SDMs) are developed and applied to estimate the global suitable marine area for mariculture. SDMs are environmental niche models that make use of geographically referenced species occurrence and environmental data to quantify the species distribution. To support the use of SDMs in this chapter, I developed a new mariculture georeferenced farm location database (MFD), which includes farm locations exclusively for mariculture in the coastal waters and Open Ocean farmed (See appendix A for details). The MFD and site selection model developed in this chapter provided the basic method and information for chapter 4 and 5 of this dissertation.

Chapter 4 aims to assess the potential impacts of climate change on the suitability of the marine area for mariculture and the potential diversity of species suitable for farming. I apply the SDMs developed in Chapter 3 to project the potential changes in a marine area suitable for mariculture and projected mariculture diversity changes in the 21st century under climate change. The projection developed in this chapter served as an input into the Generalised Additive Model developed in chapter 5.
Chapter 5 aims to develop and apply a model to project the global mariculture production potential (MPP) under climate change. Such a model is the first step towards integrating mariculture in impact, adaptation and vulnerability assessment research. The model combines outputs from chapters 2 to 4, including the status and trends of global mariculture production, and the predicted current and future marine areas suitable for mariculture. The model predicts MPP based on the EEZ mean habitat suitability index, the farm-gate price of the species, global fishmeal and fish oil production per year, the trophic level of species and total suitable marine area for mariculture.

Chapter 6 aims to extend the basic Shared Socioeconomic Pathways (SSP) framework to the mariculture food sector. Mariculture development is driven by social and economic factors, with consumer demand and preferences driving prices, costs and technology that affect mariculture productivity and viability. Given the uncertainties of future changes in these socio-economic factors, in chapter 6, I develop a set of Shared Socioeconomic Pathways for mariculture (SSPMs) to assess plausible future scenarios for sustainable mariculture under global change.

Chapter 7 provides a synthesis of this dissertation. It summarises the overall findings of this dissertation and discusses their implications for understanding the future opportunities and challenges of mariculture development under climate change. It also highlights the key limitations and uncertainties of the dissertation and its findings and offers insights into important knowledge gaps that require further research effort.
Chapter 2: Past and current status of global mariculture production: an update

2.1 Introduction

Global demand for seafood is increasing and is projected to continue for decades (Msangi et al., 2013). However, fish catches have reached their limits in most marine ecosystems, and are declining globally (Pauly and Zeller, 2016). Aquaculture is considered to be a critical component in meeting the challenge of nutritional security (Hishamunda et al., 2009; Golden et al., 2016). Although the majority of aquaculture production occurs in inland environments (FAO, 2014), there has been a growing demand in developed countries for fish and invertebrates farmed in marine and brackish water environment, i.e. mariculture (Campbell and Pauly, 2013).

Globally, mariculture production has grown from 5 million tonnes in 1990 to 21 million tonnes in 2010, with China accounting for more than 30% of total production (Campbell and Pauly, 2013). Data also show an increasing trend in the global weighted mean trophic level of the organisms that are farmed, suggesting a “farming up the food web” phenomenon in the development of mariculture (Pauly et al., 2001; Tacon et al., 2010). While bivalves account for more than 70% of the total volume of mariculture production, corresponding to a tenfold increase 1990 to 2010, the increase for finfish and crustacean was about fifty folds within the same period. Continuous mariculture production will depend on several factors including, 1) continuous supply and trade in forage fish, its products and other aquafeed ingredients (Metian and Tacon, 2009); 2) the market component interactions (e.g. price) (Asche et al., 2001); 3) human and technological development to aid expansion (Subasinghe et al., 2003); and 4) the suitability of available marine environment (Froehlich et al., 2018) to support the physiological needs of farmed species.
An essential step towards understanding the sustainability of global mariculture development is the compilation of reliable and comprehensive mariculture data. The Global Mariculture Database (GMD) of the Sea Around Us (www.searoundus.org) described by Campbell & Pauly (2013) was the first global database of marine and brackish mariculture production by taxa by each province or state for each maritime country from 1950 to 2010. GMD contains over 300-farmed species in both marine and brackish water produced in 112 maritime countries and territories with a total of 656 province or states. One of the motivations for the development of GMD by Campbell & Pauly (2013) was to examine the accuracy of other global mariculture production estimates. Thus, Campbell & Pauly (2013) compiled published data from national and provincial/state-level reports and compared the estimated mariculture production with those published by the United Nations’ Food and Agriculture Organisation (FAO). While the FAO dataset and the GMD are generally similar, inconsistencies were mainly attributed to the low accuracy in reported data in some countries such as China (Campbell and Pauly, 2013), and its taxonomic coarseness. Inaccurate data increase the uncertainties in evaluating mariculture trends and assessing the impact of mariculture on fisheries resources (Cao et al., 2015). The GMD has contributed to recent global and regional analyses of mariculture (e.g. Metian et al., 2014; Rodrigues et al., 2015). Given the rapid development in mariculture and the concerns of its sustainability, continuous improvement and updates of this database are necessary.

Farm-gate price is the price for agricultural products, including aquaculture products at the point of first sales. Given the importance of economic analyses to understand the future sustainability of global mariculture production, there is a need to develop databases on the economics of aquaculture, which should include the prices of aquaculture products and their
trends. Such databases will be particularly useful if they are harmonized with the structure of the GMD such as nomenclature of species and geographic aggregation.

In this chapter, I present an updated GMD (version 2.0) and a new farm-gate price database. These databases are an important component of this dissertation. The GMD version 2.0 is an update of the previous version with additional data for mariculture production data from 2011 to 2015, while the farm-gate price database is based on data from 1990 to 2015. The updated and new databases are essential to support the modelling and analyses in subsequent chapters of this dissertation.

2.2 Methodology and data collection

Following the same approach as used for the GMD (Campbell and Pauly, 2013) and the fisheries ex-vessel price database (Sumaila et al., 2007; Swartz et al., 2012; Tai et al., 2017), the GMD was updated with the most recent years from 2011 to 2015 using data from official statistics, published literature and unpublished reports. The GMD contains annual mariculture production by taxa, countries and sub-national units, i.e., provinces or states (Campbell and Pauly, 2013). To remain consistent with the first version of GMD, I focused on collating data on production from marine and brackish farming activities whose final products meant for direct human consumption (Campbell and Pauly, 2013). The new mariculture price (farm-gate price) database now linked to the GMD contains the farm gate-price of farmed species by country of production, by taxon and year. Prices were recorded in local and, national currencies and later converted into US dollars using the Penn World Table, version 9.0 currency exchange rate (https://www.rug.nl/ggdc/productivity/pwt/) (See Appendix C for data sources).
Missing data were imputed by the assumption that the ratio of mariculture production amongst taxa remained the same as in last year for which records were available. Additionally, for periods when production data are not available, FAO FishStat Plus data were used.

All data analyses, including descriptive statistics, mean trophic levels and production growth rates, were performed with R (R Core Team, 2018).

2.3 Results

2.3.1 Current trends in global mariculture

Global mariculture production in 2015 was estimated to be 27.6 million tonnes (Figure 2.1) with a farm-gate value of USD 85 billion. The average 5-year annual growth rate in global mariculture production was estimated to have increased from 2.9% in 2010 (2006-2010) to 4.4% (2011-2015) (Table 2.1) making the farming of fish and other aquatic organisms in marine and brackish waters the fastest growing aquaculture sub-sector in the last two decades. The top five major producing countries included China, Norway, Indonesia, Chile and Vietnam (Table 2.2). About 61% (16.9 million tonnes) of the world mariculture production in 2015 is accounted for by China, an increase from 39% (3.6 million tonnes) in 1995 (Figure 2.2). The total farm-gate production value increased from USD 11.9 billion in 2000 to USD 20 billion in 2015 (Figure 2.3). The growth rate of China’s mariculture production increased from 2.26 % in 2010 (2006-2010) to 5.04% in 2015 (2011-2015) (Table 2.1).
Figure 2. 1. Global mariculture production from 1950 to 2015.

Table 2. 1. Average annual growth rate of mariculture production (%) in different regions of the world in 2001-2005, 2006-2010 and 2011-2015.

<table>
<thead>
<tr>
<th>Region</th>
<th>Average 5-year annual growth rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>1.6</td>
</tr>
<tr>
<td>China</td>
<td>3.5</td>
</tr>
<tr>
<td>North America</td>
<td>4.3</td>
</tr>
<tr>
<td>Oceania</td>
<td>5.0</td>
</tr>
<tr>
<td>Asia (excluding China)</td>
<td>7.5</td>
</tr>
<tr>
<td>South America</td>
<td>13.3</td>
</tr>
<tr>
<td>Africa</td>
<td>36.1</td>
</tr>
<tr>
<td>World</td>
<td>4.4</td>
</tr>
</tbody>
</table>
Table 2. Annual mariculture production of the top 20 countries by total production.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>11,893</td>
<td>11,925</td>
<td>13,967</td>
<td>16,917</td>
</tr>
<tr>
<td>Norway</td>
<td>620</td>
<td>850</td>
<td>1,138</td>
<td>1,380</td>
</tr>
<tr>
<td>Indonesia</td>
<td>578</td>
<td>738</td>
<td>960</td>
<td>1,301</td>
</tr>
<tr>
<td>Chile</td>
<td>724</td>
<td>843</td>
<td>965</td>
<td>1,179</td>
</tr>
<tr>
<td>Vietnam</td>
<td>462</td>
<td>549</td>
<td>602</td>
<td>869</td>
</tr>
<tr>
<td>Japan (main islands)</td>
<td>717</td>
<td>684</td>
<td>511</td>
<td>646</td>
</tr>
<tr>
<td>India (mainland)</td>
<td>166</td>
<td>283</td>
<td>318</td>
<td>603</td>
</tr>
<tr>
<td>Thailand</td>
<td>770</td>
<td>889</td>
<td>816</td>
<td>506</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>420</td>
<td>455</td>
<td>492</td>
<td>466</td>
</tr>
<tr>
<td>Philippines</td>
<td>373</td>
<td>459</td>
<td>488</td>
<td>465</td>
</tr>
<tr>
<td>Ecuador</td>
<td>56</td>
<td>150</td>
<td>260</td>
<td>403</td>
</tr>
<tr>
<td>Mexico</td>
<td>100</td>
<td>176</td>
<td>156</td>
<td>293</td>
</tr>
<tr>
<td>Spain</td>
<td>268</td>
<td>234</td>
<td>248</td>
<td>264</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>177</td>
<td>172</td>
<td>188</td>
<td>196</td>
</tr>
<tr>
<td>USA</td>
<td>110</td>
<td>176</td>
<td>156</td>
<td>181</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>101</td>
<td>110</td>
<td>145</td>
<td>181</td>
</tr>
<tr>
<td>Canada</td>
<td>155</td>
<td>155</td>
<td>163</td>
<td>178</td>
</tr>
<tr>
<td>France</td>
<td>223</td>
<td>201</td>
<td>148</td>
<td>156</td>
</tr>
<tr>
<td>Egypt</td>
<td>141</td>
<td>221</td>
<td>117</td>
<td>145</td>
</tr>
<tr>
<td>Turkey</td>
<td>70</td>
<td>86</td>
<td>88</td>
<td>139</td>
</tr>
</tbody>
</table>
Asia, excluding China, accounted for about 5.6 million tonnes in 2015, an increase from 5 million tonnes in 2010; however, its relative contribution to the mariculture production in the world decreased from 23% to 20% during this period (Figure 2.2a). Notable mariculture production countries include in Asia: Indonesia, contributing 23.3% to Asia production, Japan (11.6%), India (10.8%), Thailand (9.1%) and South Korea (8.34%). In terms of monetary value, Asia (excluding China) accounted for USD 41 billion in 2015, an increase from USD 27.1 billion in 2000 (Figure 2.2b). Africa’s mariculture production decreased from 249,000 tonnes to about 167,000 tonnes.
(from 1.2% to 0.6% of world production) from 2006 to 2015, and its first sale value decreased from USD 580 million in 2006 to USD 540 million in 2015. Amongst African countries, the largest production was Egypt, with 234,000 tonnes in 2006, which decreased 145,447 tonnes (from 94% to 87% of Africa production) in 2015. Mariculture production from other African countries, i.e., Tunisia, South Africa and Madagascar contributed 7.9%, 1.6% and 2.1%, respectively, of the 2015 production from Africa. In Oceania, mariculture production increased from 128,000 tonnes in 2000 to about 170,000 tonnes (from 0.6% to 0.8% of world production) in 2015. The sub-sector contributed about USD 1.4 billion first sales value to Oceania countries economy in 2015, an increase from USD 790 million in 2000. Mariculture production from New Zealand increased from 85,000 tonnes in 2000 to 89,000 tonnes in 2015, while Australia’s production increased during this period from 40,000 tonnes to 80,000 tonnes. Europe’s mariculture production decreased from 9.1% of world production (2 million tonnes) in 2010 to 8.8% (2.4 million tonnes) in 2015. About USD 10 billion was generated as the first sales value in 2015, a decrease from USD 12.3 billion in 2010. The Americas accounted for 8.6% of the total volume of world mariculture production. North America generated 2.3% of world production (627,000 tonnes) in 2015, valued at USD 2.1 billion, while South America accounted for the largest share of the world production (6.3% or 1.7 million tonnes), valued at USD 10.3 billion.

Globally, the mariculture growth rate increased from 2.9% in 2010 to 4.4% in 2015 (Figure 2.3). Asia’s (excluding China) mariculture growth rate declined from 4.3% in 2010 to 2.2% in 2015 (Figure 2.3). However, China mariculture production growth rate increased from 2.3% to 5.0% within the same timeframe. Other regions with an increased growth rate include Africa (2.3% - 4.7%), Europe (2.8% to 3.6%) and South America (4.7% to 10.1%). Oceania’s and North
America’s mariculture growth rate declined from 1.9% to -0.6% and 7.5% to 2.1%, respectively, within the timeframe.

Figure 2. 3. The temporal change in the annual growth rate of mariculture in the different regions and the world.

A total of 307 taxa were recorded as farmed in mariculture from 1950 to 2015. *Crassostrea gigas* (Pacific oyster), *Ruditapes philippinarum* (Japanese carpet shell), *Penaeus vannamei* (Whiteleg shrimp), *Salmo salar* (Atlantic salmon) and *Pecten yessoensis* (Yesso scallop) are the five top species farmed in 2015 (Table 2.3). Molluscs accounted for the largest volume of total mariculture production in 2015 (46% or 12 million tonnes), while finfish and crustaceans accounted for 29% (7.9 million tonnes) and 25% (7 million tonnes) of mariculture production, respectively. In 2011, for the first time, global mariculture farmed more fed species (i.e., aqua-feed is provided to farmed organisms, include finfish and crustaceans only) than non-fed species (include molluscs only) (Figure 2.4). China farmed the largest production by volume of finfish, molluscs and crustacean between 2011 and 2015 (Table 2.4), with Norway, South Korea and Indonesia as the second-largest producers of finfish, molluscs and crustaceans respectively.
### Table 2.3. The main farmed species in production in the world from 2005 to 2015.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Phylum</th>
<th>2005</th>
<th>2008</th>
<th>2011</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crassostrea gigas</td>
<td>Pacific oyster</td>
<td>Mollusca</td>
<td>4,453</td>
<td>4,019</td>
<td>4,408</td>
<td>5,202</td>
</tr>
<tr>
<td><em>Ruditapes philippinarum</em></td>
<td>Japanese carpet shell</td>
<td>Mollusca</td>
<td>2,909</td>
<td>3,108</td>
<td>3,638</td>
<td>4,014</td>
</tr>
<tr>
<td>Penaeus vannamei</td>
<td>Shrimp</td>
<td>Arthropoda</td>
<td>1,178</td>
<td>1,803</td>
<td>2,402</td>
<td>3,112</td>
</tr>
<tr>
<td>Salmo salar</td>
<td>Atlantic salmon</td>
<td>Chordata</td>
<td>1,232</td>
<td>1,449</td>
<td>1,732</td>
<td>2,384</td>
</tr>
<tr>
<td><em>Pecten yessoensis</em></td>
<td>Yesso scallop</td>
<td>Mollusca</td>
<td>1,114</td>
<td>1,363</td>
<td>1,426</td>
<td>2,037</td>
</tr>
<tr>
<td>Chanos chanos</td>
<td>Milkfish</td>
<td>Chordata</td>
<td>568</td>
<td>657</td>
<td>875</td>
<td>1,016</td>
</tr>
<tr>
<td>Mytilus coruscus</td>
<td>Korean mussel</td>
<td>Mollusca</td>
<td>761</td>
<td>545</td>
<td>775</td>
<td>887</td>
</tr>
<tr>
<td><em>Sinonovacula constricta</em></td>
<td>Constricted tagelus</td>
<td>Mollusca</td>
<td>676</td>
<td>742</td>
<td>745</td>
<td>794</td>
</tr>
<tr>
<td>Penaeus monodon</td>
<td>Giant tiger prawn</td>
<td>Arthropoda</td>
<td>724</td>
<td>725</td>
<td>685</td>
<td>708</td>
</tr>
<tr>
<td>Anadara granosa</td>
<td>Granular ark</td>
<td>Mollusca</td>
<td>440</td>
<td>419</td>
<td>405</td>
<td>440</td>
</tr>
<tr>
<td>Mytilus galloprovincialis</td>
<td>Mediterranean mussel</td>
<td>Mollusca</td>
<td>347</td>
<td>302</td>
<td>321</td>
<td>323</td>
</tr>
<tr>
<td><em>Mytilus chilensis</em></td>
<td>Chilean mussel</td>
<td>Mollusca</td>
<td>88</td>
<td>187</td>
<td>289</td>
<td>289</td>
</tr>
<tr>
<td>Rapana sp</td>
<td>Purple whelk</td>
<td>Mollusca</td>
<td>-</td>
<td>225</td>
<td>203</td>
<td>243</td>
</tr>
<tr>
<td><em>Oncorhynchus mykiss</em></td>
<td>Rainbow trout</td>
<td>Chordata</td>
<td>217</td>
<td>276</td>
<td>326</td>
<td>226</td>
</tr>
<tr>
<td>Scylla serrata</td>
<td>Giant mud crab</td>
<td>Arthropoda</td>
<td>23</td>
<td>150</td>
<td>158</td>
<td>223</td>
</tr>
<tr>
<td><em>Apostichopus japonicus</em></td>
<td>Japanese sea cucumber</td>
<td>Echinodermata</td>
<td>0</td>
<td>0</td>
<td>138</td>
<td>206</td>
</tr>
<tr>
<td><em>Mytilus edulis</em></td>
<td>Blue mussel</td>
<td>Mollusca</td>
<td>236</td>
<td>204</td>
<td>191</td>
<td>189</td>
</tr>
<tr>
<td><em>Oncorhynchus kisutch</em></td>
<td>Coho salmon</td>
<td>Chordata</td>
<td>117</td>
<td>105</td>
<td>160</td>
<td>168</td>
</tr>
<tr>
<td>Dicentrarchus labrax</td>
<td>European bass</td>
<td>Chordata</td>
<td>100</td>
<td>135</td>
<td>138</td>
<td>167</td>
</tr>
<tr>
<td>Sparus aurata</td>
<td>Gilt-head bream</td>
<td>Chordata</td>
<td>111</td>
<td>124</td>
<td>138</td>
<td>163</td>
</tr>
</tbody>
</table>
Figure 2.4. Time-series of mariculture production of finfish and crustaceans (fed, red line) and molluscs (non-fed, blue line) from 1950 to 2015.
Table 2. The top five countries in mariculture production (total production from 2011 to 2015) for each species group: finfish, molluscs and crustaceans.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Annual production (x1,000 tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Finfish</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>China</td>
<td>11,612</td>
</tr>
<tr>
<td>2</td>
<td>Norway</td>
<td>6,405</td>
</tr>
<tr>
<td>3</td>
<td>Chile</td>
<td>4,112</td>
</tr>
<tr>
<td>4</td>
<td>Indonesia</td>
<td>2,896</td>
</tr>
<tr>
<td>5</td>
<td>Philippines</td>
<td>1,907</td>
</tr>
<tr>
<td></td>
<td>Molluscs</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>China</td>
<td>49,694</td>
</tr>
<tr>
<td>2</td>
<td>South Korea</td>
<td>1,680</td>
</tr>
<tr>
<td>3</td>
<td>Chile</td>
<td>1,376</td>
</tr>
<tr>
<td>4</td>
<td>Spain</td>
<td>1,027</td>
</tr>
<tr>
<td>5</td>
<td>Thailand</td>
<td>965</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>China</td>
<td>16,312</td>
</tr>
<tr>
<td>2</td>
<td>Indonesia</td>
<td>2,626</td>
</tr>
<tr>
<td>3</td>
<td>Vietnam</td>
<td>2,392</td>
</tr>
<tr>
<td>4</td>
<td>Thailand</td>
<td>2,121</td>
</tr>
<tr>
<td>5</td>
<td>India</td>
<td>1,684</td>
</tr>
</tbody>
</table>
The weighted mean trophic level of global mariculture production continued to increase since the GMD was first published (Figure 2.5). In 2015, the globally weighted mean trophic level was 2.54, increased from 2.47 MTL in 2010. Historically, the average mean trophic level from 2005 to 2015 is 2.49% higher than that in 1970. From 1950 to 2015, mean trophic level fluctuated substantially in the 1990s, with a sharp decrease in 1993, which later increased again by 1999.

Regional, Africa was the only region with a decline in MTL from 2.54% in 2010 to 2.5% in 2015. Region with increased MTL includes; Asia (excluding China) 2.52% to 2.57%, Europe 3.59% to 3.73%, Oceania 2.78% to 3.02%, China 2.22% to 2.25%, North America 2.79% to 2.88% and South America 3.01% to 3.36%.

Figure 2.5. Temporal change in the mean trophic level of mariculture production in the different region and the world, 1950-2015.
2.3.2 Global farm-gate price trends

The farm-gate price database consists of 62,210 unique prices for 307 taxa covering 25 years (1990-2015) in 112 countries and territories where mariculture was recorded to occur in GMD. A total of 5,598 records (9%) are raw farm-gate price data, and 56,612 records are estimated farm-gate price from reported farm-gate value (see Appendix C for sources).

Overall, there is an increasing price trend in farm-gate price over time for finfish and crustaceans, while molluscs decreased to an all-time low in 2003 (Figure 2.7). The farm-gate price of mollusc remained relatively stable from 1990 to 2015 (Figure 2.6).
Global mariculture farm-gate value increased from USD 28.5 billion in 1990 to USD 85 billion in 2015. The farm-gate value of finfish increased from USD 15 billion in 2000 to about USD 36 billion in 2015, while the crustaceans total farm-gate value of USD 21 billion decreased in 1995 to USD 11 billion in 2013; this value later increased to about USD 27 billion in 2015. Despite a lower farm-gate price compared to other species groups, farm-gate value of molluscs increased from USD 13 billion in 2003 to about USD 21 billion in 2015. Regionally, Asia (excluding China) accounted for about 50% (USD 41 billion) of global farm-gate value in 2015 (Figure 2.7). China accounted for about 24% (USD 20 billion) of global farm-gate value, while in
Europe, mariculture contributed about USD 9 billion to the total GDP in 2015. South America accounted for 12% (USD 10 billion) of total global mariculture production value, while North America generated USD 2.1 billion in 2015. Oceania accounts for 1.7% of the global mariculture value (USD 14 billion) while Africa produced USD 541 million in 2015.

**Figure 2.7.** The proportion of farm-gate value contributed by each world region. China is reported separately because of their large mariculture production.

### 2.4 Discussion

Asia, particularly China, was the main driver of the continuous increase in global mariculture production from 2010 since the first GMD version (Campbell and Pauly, 2013). The growth of China’s mariculture industry was partly stimulated by several aspects of its national policies (Hishamunda and Subasinghe, 2003; FAO, 2018), particularly open market policies. Also, there is a large demand for consumption of mariculture products in China, which contributed to the growth of mariculture both in China and elsewhere (Li et al., 2011). China has also extended
its technological development to the aquaculture industry, thereby increasing the diversification of species and systems (Zhao and Shen, 2016), which boost seafood production from mariculture.

Mariculture growth has been supported by aquaculture production development programs implemented by various countries or international organisations. Such programs were common in Africa and Small Island Developing States (SIDS) that aimed to promote export-oriented mariculture rather than local nutritional and food security (Rivera-Ferre, 2009). Hence, such programs supported the development of mariculture production of species with high trophic level and value that were not tailored to local consumer preferences or affordability.

Other social-political-economic factors may also play a role in affecting mariculture production. These factors may include regional conflicts that affect mariculture operations, e.g., Africa’s production was affected by the strong decline of Egypt’s mariculture production, which may have been due to the Arab Spring in the first half of 2011 (Misselhorn, 2005; Lagi et al., 2011; Veninga and Ihle, 2018).

While the updated GMD and the new farm-gate price database can be used to facilitate mariculture research, such use should consider the key assumptions and uncertainties associated with these databases. First, in most countries, particularly in Africa and small Islands countries, production and farm-gate value were available only at the national/country level or high levels of taxonomic classification and for a specific time only. For the farm-gate price database, the trends shown in this chapter are a weighted average across countries and species, and thus, the trends may not reflect trends for specific countries or taxa. Also, a larger percentage of the farm-gate prices estimated in this database are from the reported farm-gate value of species by producing countries. There is a possibility that the reported value is the ‘market value’ (i.e., including
transportation cost and marketing cost) instead of the actual gate price. Also, the data sources used in the construction and updating of GMD may be biased towards those that are available publicly and are reported in English. Thus, future work should dedicate more effort on improving data collection with the help of local researchers who can have access to aquaculture industry reports and other documents, particularly those that are reported in languages other than English. Also, there is a lack of clarity in the reporting process and documentation of some aquaculture statistics. In some countries, higher taxonomic levels, e.g., families are reported rather than species. For the farm-gate price database, there is a general lack of available data, and thus more effort in collecting primary data is needed.

Notwithstanding the gaps and uncertainties of the GMD and the farm-gate value databases, there is a wide range of their potential applications to support regional and global mariculture evaluation and analysis. These databases serve as key inputs in the mariculture modelling presented in this dissertation.
Chapter 3: Global estimation of areas with suitable environmental conditions for mariculture species

3.1 Introduction

Fish and other aquatic organisms, particularly from the marine environment, strongly contribute to the nutritional security and well-being of people. Many coastal communities in tropical developing countries are highly dependent on fish as an important source of nutrients (Roos et al., 2007; Tacon and Metian, 2013; Golden et al., 2016). Given projected increases in the world's population over the next decades (UN, 2019), jointly with increased inclusion of seafood in diets (Golden et al., 2016), global demand for seafood is expected to increase (Delgado, 2003). Although, there may be some room for expansion of fisheries if fish stocks are rebuilt (Costello et al., 2012), their catches have reached their maximum in most parts of the global oceans (Watson et al., 2015; Pauly and Zeller, 2016). Thus, increasing food production from aquaculture is widely considered the major approach to meet the rising demand for seafood (Naylor et al., 2000; Beveridge et al., 2013; Belton and Thilsted, 2014).

A range of environmental and social-economic factors influences the sustainable development of mariculture. Most mariculture involves growing fish or invertebrates in nets or cages that are submerged, allowing for free water exchange with the surrounding marine environment (Islam, 2005; Benetti et al., 2010). Thus, the survival and growth rates of farmed organisms are directly influenced by natural environmental conditions (Pillay, 2008). However, a number of other factors play an important role in determining the actual production capacity and sustainability. These include but are not limited to: the carrying capacity of the farming area (Byron et al., 2011), feed ingredients, e.g. the demand for forage fish in aquafeeds (Tacon and Metian, 2009; Cao et al., 2015; Pauly and Zeller, 2016; Cashion et al., 2017) or plant proteins (Troell et
al., 2014b), the development of closed life cycles farming techniques to reduce the need for wild-caught juveniles and/or broodstock for restocking (Ottolenghi et al., 2004; Hermansen and Dreyer, 2008), other technological developments that reduce the environmental impacts of mariculture (Troell et al., 2009); and the quality of governance to ensure sustainable mariculture practices (Hofherr et al., 2015).

An important first step towards better describing the space available for sustainable mariculture production is the identification of marine areas that offer suitable environmental conditions for currently farmed species. Since most ocean-based mariculture operations use open facilities in which the farmed organisms are exposed to natural environmental conditions, the physical and chemical properties of the waters affect the organisms’ growth and survivorship, and consequently, their productivity. Here, suitable environmental conditions refer to the area of the ocean that can support the physiological needs of farmed species for sustainable mariculture production (Tidwell and Allan, 2001). Environmental preferences of (farmed) marine species can be approximated and mapped using species distribution models (SDMs). Based on the environmental niche theory (Hutchinson, 1959), this modelling approach consists of quantitatively describing the relationship between a species’ observed occurrence records and various parameters that describe its environment. Such a relationship can be developed using historical occurrence records of the species in both the natural and farmed environments. SDMs can be applied to predict species’ distribution in the past, present and future (Guisan and Zimmermann, 2000b; Elith and Leathwick, 2009). Until now, SDMs have only be applied in biodiversity and fisheries-related research.
The use of SDMs is particularly suited to marine ectotherms and thus have a spatial distribution that is tightly correlated to environmental conditions (Cheung et al., 2010; Cheung et al., 2015; Jones and Cheung, 2015).

This study aims to predict the spatial extent of the area that is suitable environmentally for mariculture. I applied four SDMs: Ecological Niche Factor Analysis (ENFA) (Basille et al., 2008), the Non-Parametric Probabilistic Ecological Niche (NPPEN) (Beaugrand et al., 2011), Maximum Entropy (MAXENT) (Phillips et al., 2006) and Surface Range Envelope (SRE) (Busby, 1991), to quantify the environmental niche of the presently important farmed species and project their habitat suitability index (HSI) over the global ocean based on current environmental conditions. I focused on coastal and open water farming systems only. Based on the predicted HSI, the total area of the world’s exclusive economic zones (EEZ) that is suitable for farming marine species was calculated. I examined the variation among models and compare it with the mean predictions across models to highlight where predictions were most robust to variations. I then evaluated model projection uncertainties and estimated the total area that would be suitable for mariculture. Finally, I discussed the implications of these results for future mariculture development.

### 3.2 Material and methods

#### 3.2.1 Biotic data

The list of farmed species was obtained from the Sea Around Us mariculture database (www.seaaroundus.org). The database is derived largely from the Food and Agricultural Organisation (FAO) database, with additional information from national statistics to subdivide annual mariculture production into sub-national units (e.g., provinces, states), in addition to countries and taxa, for the period 1950 to 2015. I extracted the species’ names of all fish and
invertebrates reported in the database (307 in total). Records reported at higher than species level were excluded from this analysis. Following the minimum occurrence data requirements for SDM (Elith et al., 2006), I only retained species that occurred in more than seven sub-national units. This is to ensure a greater model accuracy with higher numbers of occurrence locations. Thus, this study focused on a total of 102 species (57 Chordata, 15 Arthropods, 29 Mollusca and 1 Echinodermata) (See Appendix A for list of species included in this dissertation). Although seaweed mariculture contributes substantially to global production, I do not include seaweed in this study because of the lack of geospatial data on seaweed mariculture locations.

Altogether, the species included in the analysis contributed to about 80% of global mariculture production. Species’ ecological information, including maximum depth, minimum depth, trophic level, preferred biome (Reygondeau et al., 2013) and habitat, were obtained from FishBase (http://www.fishbase.org/) and the Encyclopaedia of life (http://eol.org/).

To obtain a representative spatial distribution of each farmed species and quantify its environmental niche, two databases were developed. The first consisted of natural occurrence records (i.e., from the wild) for all 102 species from a number of open-source databases: Ocean Biogeographic Information System (OBIS, http://www.iobis.org/), Global Biodiversity Information Facility (GBIF, http://www.gbif.org/), FishBase (http://www.fishbase.org/) and the International Union for the Conservation of Nature (IUCN, http://www.iucnredlist.org/technical-documents/spatial-data). For each species, I removed duplicate records of occurrences among databases and records for which geographic information was not available.

Secondly, I developed a georeferenced occurrence database exclusively for mariculture (i.e., coastal and open-ocean). Using all sub-national units where farms were recorded in the Sea Around
**Us** mariculture database, I identified any mariculture installations (pens, cages and lines) based on satellite photos available from Google Earth ([http://www.google.com/earth/](http://www.google.com/earth/)). The coordinates were extracted for each installation by using the Google Earth Placemark tool (Trujillo et al., 2012) (Figure 3.1).

All species’ natural occurrence and mariculture location records were converted to a binary database of presence or absence and rasterised on a regular spatial grid of 0.5° latitude by 0.5° longitude over the global ocean.

![Geo-referenced world mariculture locations for all farmed species in the model.](image)

**Figure 3.1.** Geo-referenced world mariculture locations for all farmed species in the model.
3.2.2 Environmental data

I collected eight environmental parameters: temperature, dissolved oxygen concentration, chlorophyll-\(a\) concentration, salinity, pH, silicate concentration, current velocity and euphotic depth. Annual climatology for the period 1955-2012 for temperature, salinity, dissolved oxygen concentration and silicate concentration was obtained from the World Ocean Atlas 2013 (http://www.nodc.noaa.gov/OC5/woa13/). Euphotic depth and chlorophyll-\(a\) concentration annual climatology for the period from 1998 to 2012 were downloaded from the Ocean Colour website (http://oceancolor.gsfc.nasa.gov). I obtained 10-year averaged ocean current velocity data (1992-2002) from the Estimating the Circulation and Climate of the Ocean (ECCO) Project (http://www.ecco-group.org). Surface and bottom pH values were extracted from the Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM-2G) and averaged over the period 1970-2000. All environmental data were interpolated using bilinear methods (Legendre and Legendre, 1998) over the global ocean (189.75 °W to 179.75 °E and 89.75 °N to 89.75 °S) on a regular spatial grid of 0.5° latitude by 0.5° longitude (the same as occurrence rasterized data) and for two vertical layers: surface (0-10m) and sea bottom depth where available.

3.2.3 Modelling habitat suitability

Habitat suitability was predicted for each farmed species on the 0.5° by 0.5° grid of the global ocean using species distribution models (SDMs). Firstly, biotic and environmental data were harmonised based on the regular spatial grid coordinates with data on occurrences in natural and mariculture environments. Secondly, the most critical environmental parameters to model the farmed marine species’ distribution was determined using the eigenvalue diagram implemented in the Ecological Niche Factor Analysis (ENFA) (Basille et al., 2008). The diagram was constructed
based on the departure of the ecological niche from the mean habitat for each species, thus identifying the species’ preference for particular environmental parameters among the whole set of parameters (Figure 3.2). I selected the most important set of environmental parameters by identifying the direction in which the ‘specialisation’ was highest. The specialisation is a measure of the narrowness of the niche, i.e., the higher the specialisation, the more restricted the niche. I then used these selected parameters for all SDM in this study. Finally, the habitat suitability for each species (mariculture and natural occurrence) was predicted using four SDMs. A multiple-model approach was used to explore the variations and uncertainty of predictions from different SDMs (Jones et al., 2013; Jones and Cheung, 2015).

Figure 3.2. ENFA biplot with the x-axis (marginality) and y-axis (specialisation). The white dot within the dark area represents the centre of used area while the light area is the available niche. The arrows are projections of oceanic parameters based on mariculture locations of the species (a) Pacific cupped oyster (*Crassostrea gigas*) (b) Cobia (*Rachycentron canadum*) (c) Atlantic salmon (*Salmo salar*) (d) Giant tiger shrimp (*Penaeus monodon*).
The four SDMs predict species distributions based on different algorithms and assumptions. The first SDM, ENFA, is an analysis that uses multivariate statistics to assess species’ habitat selection by providing the realised niche measurement within the available hyper-space from two estimates: the marginality, that identifies a species’ preference for given environmental conditions, and its specialisation (i.e., the species’ sensitivity to variations in its optimum environment) (Basille et al., 2008). The lower the marginality, the less the niche deviates from available conditions; the higher the specialisation, the more restricted the niche (Hirzel et al., 2002). The second model, the Non-Parametric Probabilistic Ecological Niche (NPPEN) (Beaugrand et al., 2011), is based on a simplification of the Multiple Response Permutation Procedures (MRPP) using the Generalised Mahalanobis distance. The other two SDMs, Maximum Entropy (MAXENT) (Phillips et al., 2006) and Surface Range Envelope (SRE) (Busby, 1991), use various numerical procedures. MAXENT estimates the ratio of a species’ presence site to the study area and then calculates the probability of occurrence through a logistic transformation (Elith et al., 2011). SRE is an environmental envelope model that identifies cells which have environmental values that fall within the range of values measured from the presence data (Hernandez et al., 2006). All the SDMs use presence-only data to determine a species’ environmental distribution. Each SDM was then applied to predict a species’ habitat suitability index (HSI) - an index that scales from 0 to 1 to indicate the environmental suitability of the selected environmental conditions in each spatial cell for each studied species.
3.3 Model testing

The robustness of the SDM outputs was tested by comparing the predicted HSI with reference records of species occurrences. Mariculture and natural occurrence data were analysed separately and divided into two datasets: 75% of all records were used for training purposes to develop each SDM and calculate each species’ HSI. The remaining 25% of the data were used for model evaluation. Specifically, the Area Under the Receiver Operating Characteristic Curve (AUC) of each set of model predictions was calculated using the ROCR package in R (Sing et al., 2007). The AUC values range from 0 to 1, with 0.5 indicating that the model is no better than a random sample of values and 1 indicating that the model has high predictive power.

The correlation between the HSI predictions from the natural and mariculture occurrence data was examined. For each species, I fitted a linear model to predicted HSI from mariculture and natural occurrences as dependent and independent variables, respectively. Then I cross-validated this statistical relationship by applying a generalised linear model to the combined species HSI; this assumed binomial error distribution. The degree of overdispersion for proportional data from residual deviance was calculated and then fitted a quasi-binomial distribution to account for the overdispersion (Crawley, 2005). I set a minimum predicted HSI for each species as the value below which a species was considered to be absent. This approach used species-specific minimum HSI thresholds instead of a fixed threshold for all species, as used by Jones and Cheung (2015). The thresholds were identified by quantifying a species’ “prevalence”, i.e., the fraction of cells at which the species is present (Phillips et al., 2009); this represented the minimum HSI threshold for that species, and tested mariculture location HSI (presence) versus natural occurrence HSI (absence). The predictive values of habitat suitability for mariculture below the prevalence value were assigned a 0 and predicted HSI values higher than the prevalence value were assigned values of 1.
3.4 Identifying potential mariculture area

The first criterion that used to define potential mariculture area in this study was the suitability of the environment for farmed species. For an area to be suitable for mariculture, it must meet the minimum environmental conditions for the growth and survival of farmed species. Thus, for each farmed species, its potential mariculture area must have an HSI above its minimum threshold (i.e., prevalence).

The second criterion was assuming that mariculture operations would not extend beyond the area of sovereign nations’ jurisdiction. Thus, the potential mariculture area was constrained to be within countries’ Exclusive Economic Zone (EEZ). I also assumed that mariculture could only be found in spatial cells with a current velocity between 10 cm·s\(^{-1}\) and 100 cm·s\(^{-1}\) (Kapetsky et al., 2013b). The low current would result in more rapid food depletion (less particulate organic matter flow) and less efficient production (Ferreira et al., 2007), less waste removal (feed and organic waste), and high benthic impact in finfish aquaculture (Borja et al., 2009). In contrast, strong currents can damage farm structures and holding facilities (Benetti et al., 2010) and affect the growth of farmed fish through skeletal malformations (Chatain, 1994). Furthermore, as most marine protected areas (MPAs) do not allow mariculture activities, they were not considered as suitable future mariculture areas (Table 3.1).

<table>
<thead>
<tr>
<th>Justification</th>
<th>Criteria</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Political boundary</td>
<td>Within exclusive economic zone (EEZ)</td>
<td>200nm (370.4km)</td>
</tr>
<tr>
<td>Disturbance by strong ocean currents</td>
<td>Within a range of ocean suitable current velocities</td>
<td>Current velocity between 10cm.s(^{-1}) and 100cm.s(^{-1})</td>
</tr>
<tr>
<td>Conflicting use of waters</td>
<td>Area outside of marine protected areas</td>
<td>Potential areas exclude marine protected sites</td>
</tr>
</tbody>
</table>
The total suitable mariculture area for the 102-farmed species considered for each model was calculated and derived an overall multi-model weighted average (each model contributed to the final output based on its AUC value). I also estimated the number of species that were predicted to be suitable for mariculture in each spatial cell. Then, I compared the spatial distribution of potential mariculture area and species richness of the 20-farmed species with the highest cumulative production from 1950 to 2010.

3.5 Results

3.5.1 Prediction of HSI

The predicted mariculture and natural habitat suitability index generally agree with observed occurrences. Almost all predicted species distributions for all species and models had AUC values greater than 0.7 (Figure 3.3a and b). The AUC values varied among models, with predictions from SRE having a median AUC across species ~ 0.8, and predictions from MAXENT scoring the highest median AUC values. The 25th and 75th percentiles of the estimated prevalence value for each species ranged from 0.30 to 0.62.
3.5.2 Potential mariculture area and species richness

Overall, I found a significant and positive relationship between the environmental niche of mariculture locations and that of farmed species’ natural occurrences. Across all farmed species, I found a significant and positive linear relationship between mariculture occurrence-based (y) and natural occurrence-based (x) HSI (y=0.27x + 0.54, p < 0.001) (Figure 3.4a). For each individual species, the adjusted R-square values of the regression between mariculture and natural-based HSI
were above 0.50, with a mean of 0.66 (Figure 3.4b). Species that showed the strongest relationship between the mariculture-based and natural-based HSI were Red drum (*Sciaenops ocellatus*), Peruvian scallop (*Argopecten purpuratus*) and Pacific cupped oyster (*Crassostrea gigas*) ($R^2 = 0.90, 0.88$ and 0.86, respectively).

Figure 3.4. Relationship between predicted mariculture habitat suitability index (HSI) and natural occurrence habitat suitability index. (a) Regression of global predicted mariculture HSI and natural occurrence HSI ($p<0.001$). (b) Histogram of adjusted $R^2$ of individual species’ regression analysis with a mean value of 0.66.
The predicted environmentally suitable areas for mariculture with high agreement among the four SDMs are found between 66.5° N and 66.5° S (Figure 3.5). Based on the weighted average predictions (AUC as the weight) from the four SDMs, the total suitable mariculture area for the 102 species was estimated at 72 million km² (Figure 3.6). Predictions from ENFA result in the largest suitable marine area (107 million km²) while NPPEN yielded the lowest value (91.5 million km²) (Figure 3.8). Sixty-six million km² of this area is suitable for finfish, 39 million km² for crustaceans and 31 million km² for molluscs. This included areas currently used for mariculture purposes. Areas that were predicted as unsuitable for the mariculture of any species include Antarctica and pockets around the Arctic region.

Mariculture species richness was highest in potential mariculture areas between 25° N and 25° S (Figure 3.8) and include the southwestern Atlantic coast (species richness = 30 – 45 among models) and West Africa (species richness = 35 – 40 among models). Other notable areas with high mariculture species richness included the Gulf of Mexico, the Caribbean Sea, the East China Sea, the Yellow Sea, the Sea of Japan and the Banda Sea off the coast of Timor-Leste. However, despite results showing high species richness for these potential mariculture areas, most of the species were not being farmed in these regions.
Figure 3.5. Predicted suitable marine area for mariculture and the agreement among SDMs. Blue - high agreement (4 models), Yellow - moderate agreement (3 models), Green - low agreement (2 models) and Red – very low agreement (1 model).
Figure 3.6. Potential marine area suitable for mariculture production and current versus potential farmed species richness. (a) Total predicted suitable marine areas for mariculture in blue and unsuitable marine areas in red based on an average of four different species distribution models; (b) Comparison between present numbers of species farmed in different countries with potential numbers of farmed species based on model outputs.
Figure 3. 7. Predicted marine area suitable for mariculture from four species distribution models: ENFA, MAXENT, NPPEN and SRE; and weighted Multi-model. ENFA predicted the highest area with 107 million km$^2$ while the Multi-model predicted 72 million km$^2$.

Figure 3. 8. Latitudinal predicted species richness (a) global mariculture species richness (b) Finfish (c) Crustaceans (d) Molluscs.
Specifically, I found a large potential area for finfish mariculture in the tropics, between 20 °N and 20 °S (mariculture species richness between 5 and 30 spp.) (Figure 3.9). In contrast, molluscs were predicted to be the dominant mariculture group in the temperate areas (23.0 ° to 66.5 ° in both the northern and southern hemispheres), with mariculture species richness of 3 to 15 spp. Large potential areas for crustaceans mariculture were predicted in waters within 23° N to 25° N and 23° S to 25° S, with predicted mariculture species richness of 2 to 12 spp. and 3 to 11 spp., respectively.
Figure 3.9. Global predicted potential mariculture area and regional farmed species richness for (a) finfish (66 million km$^2$), (b) crustaceans (39 million km$^2$), and (c) molluscs (31 million km$^2$).
3.5.3 Species and country-level comparisons

Predicted potential mariculture area varied across the most important farmed species. Milkfish (*Chanos chanos*) was predicted to have the largest suitable farming area (21 million km$^2$), while hooded oyster (*Saccostrea cucullata*) was predicted to have the smallest area (0.2 million km$^2$) amongst the 20-species selected for comparison (Fig 2.10). I found a minimum of 10% difference between the number of countries currently practising mariculture and those with the potential for marine farming production. For example, the predicted mariculture potential area was 16% larger than the area where mariculture was reported to have occurred for Atlantic salmon (*Salmo salar*). For Cobia (*Rachycentron canadum*) and Pacific cupped oyster (*Crassostrea gigas*), reported mariculture area was 80% and 46% below their predicted spatial extent, respectively.
Figure 3.10. Total predicted potential mariculture area for 20 of the most cultured species based on cumulative production from 1950-2010. (a) Classification by total potential marine areas suitable for farming. (b) Classification by total present and potential number of countries.
3.6 Discussion

3.6.1 Overall model performance

By using an ensemble of SDMs (Jones and Cheung, 2015), this study was able to explore the structural uncertainty of the predicted mariculture species distributions and environmental suitability. Projections from ENFA and SRE showed considerable variation in comparison with MAXENT and NPPEN. MAXENT and NPPEN had the highest AUC values. For the former approach, this may be due to the model’s weighting of input variables (Jones and Cheung, 2015), which prevented over-fitting of the model by determining how much the likelihood should be penalised (Phillips and Dudík, 2008). NPPEN measures the correlation between species’ occurrence and distribution, thus avoiding random quantile class selection to allow direct estimation of species occurrence (Beaugrand et al., 2011). The multi-SDM approach explored the uncertainty due to discrepancies among models, thereby capturing the full range of potential suitable marine areas for mariculture.

The relevance of the set of environmental factors identified by the modelling algorithms applied here to best predict mariculture areas are supported by empirical knowledge (Ross et al., 1993; Karthik et al., 2005; Longdill et al., 2008; Kapetsky et al., 2013a). For example, the physiology of farmed species is affected by changes in temperature (Cochrane et al., 2009). Optimal temperature determination for farmed species growth is important to practice in mariculture (Imsland et al., 1996). Also, oxygen is an important factor affecting the growth of fishes (Pauly, 2010; Pauly and Cheung, 2017) and dissolved oxygen level is an important consideration in determining the holding capacity of fish farms (Merino et al., 2007; Besson et al., 2016). Salinity influences the growth some of farmed species, with salinity levels above 25
Practical Salinity Unit (PSU) leading to high mortality and retarded growth in farmed scallop (*Pecten maximus*) (Christophersen and Strand, 2003; Duncan et al., 2016) while such salinity level was associated with increased growth performance in seabream (Tandler et al., 1995). Moreover, primary production and suspended particulate organic matter or seston, indicated by chlorophyll *a* concentrations and silicate, respectively, are food sources for molluscs (Pilditch et al., 2001; Newell, 2004). Thus, their concentration is expected to affect the growth of farmed molluscs.

### 3.6.2 Mariculture opportunities and limitations

Overall, these findings suggest that the global ocean environmentally suitable area for mariculture is much larger than the area in which mariculture is currently practised. Particularly, most offshore areas considered environmentally suitable are not being used for farming activities. These results, therefore, suggest that the lack of environmentally suitable area for mariculture is not the main limiting factor for the expansion of mariculture (Hofherr et al., 2015) in most regions of the world. Instead, other factors such as the socio-economics of producing countries, including capacity and political instability; technology, its availability and cost-effectiveness (Theodorou, 2010); aquafeed availability (Tacon and Metian, 2008; Naylor et al., 2009; Troell et al., 2017b); aquaculture development-related policies (Burbridge et al., 2001; Broitman et al., 2017) and competition for space within an EEZ for instance; shipping, oil and gas, as well as tourism all play major roles in the development of mariculture operations and their future expansion.

The conclusion about the area suitable for mariculture and its limitation for its utilisation for mariculture operations agree with a related study that employed different methods to estimate the potential global area for mariculture (Gentry et al., 2017). Specifically, Gentry et al. (2017) applied more constraints than this study in estimating available ocean area for mariculture, resulting in a
lower estimate. For instance, this study does not consider water depth as a limiting factor to define environmentally suitable areas for finfish, as the use of submersible cages is widespread for a number of farmed species (e.g., salmon, cobia) (Brown, 2010). In this case feed development, socio-economic and technological factors may represent a constraint to farming rather than water depth itself (Troell et al., 2017b). The use of multiple approaches to predict suitable mariculture area should be encouraged so that the uncertainties associated with such predictions can be better characterised.

Regionally, the results show that the difference between the predicted environmentally suitable area for mariculture and the extent of current mariculture activities is largest in Africa, the Caribbean and along the Atlantic coast of South America. These regions are predicted hotspots for mariculture species richness (60% of the 102 species), yet actual mariculture operations appear to be relatively limited, accounting for only 1.3% of global mariculture production (Campbell and Pauly, 2013; FAO, 2014). Factors such as poor economic conditions, lack of supporting infrastructure (Gabriel et al., 2007), political instability, limited foreign investment in the sector (Ridler and Hishamunda, 2001) and inadequate value chain linkages (Troell et al., 2014b) in many countries of these regions may have impeded mariculture development.

China, in contrast, is presently using the largest extent of its suitable area for marine aquaculture. The country has a long history of aquaculture, going back 2500 years (Hishamunda and Subasinghe, 2003). Owing to reforms in the late 1970s, China’s aquaculture industry has benefited from open market policies. Also, the fact that China accounts for one-quarter of the global fish demand has provided aquaculture with a market suitable for its expansion. However, this expansion might exert more pressure on marine fisheries as China’s aquaculture industry accounts for one-third of global fishmeal production (Cao et al., 2015).
Concerns regarding the broader environmental sustainability of mariculture may limit the sector’s expansion. Particularly, the focus on farming carnivorous species will increase the demand for fish feeds, adding to the stress on forage fish and, as well on the small fish caught by non-selective trawling (Tacon and Metian, 2009). Fishmeal and oil are the products of reduction fisheries and the two essential inputs into aquafeed since they are highly digestible and essential sources of amino acids (Gómez-Requeni et al., 2004b; Moe et al., 2007). While successful partial replacement of fishmeal with plant and other sources (e.g. insects, yeast and algae) has been tested and used in aquafeed (Gatlin et al., 2007; Turchini et al., 2010), there are still challenges remaining for using fully plant-based feed source particularly for high value species such as Atlantic salmon (Naylor et al., 2009). High-quality plant-based ingredients used in feeds must also, in the long run, be replaced by innovative resources not competing with human food.

Affordable and efficient technology can also contribute to the expansion of mariculture. Significant advances have been achieved in land-based systems designed to reduce nutrient load discharges, and farmed species escapes, as well as improve disease management (Tal et al., 2009; Martins et al., 2010; van Rijn, 2013). In coastal finfish and shellfish mariculture systems, a variety of cages are being developed to withstand high wave actions and reduces escapes in offshore areas (Halwart et al., 2007b; Benetti et al., 2010). Such advances will be necessary given predictions of increased storm activity in the future (Pickering et al., 2011b; Callaway et al., 2012). For crustaceans, such advances are lagging and a number of significant hurdles will need to be overcome for these to become operational. In addition, integrated multi-trophic aquaculture systems (IMTA) where lower trophic level species, such as seaweed and bivalves, are farmed together with finfish (Troell et al., 2009) can maximise inorganic and organic nutrient waste recycling, thereby reducing the environmental footprint of mariculture farms. While these systems
hold much promise, large commercial IMTA farms are still uncommon.

Strong environmental governance is also needed to regulate and ensure the sustainable development of mariculture. Aquaculture activities are regulated by law in many countries (e.g., Canada, China, Norway and the Philippines; Van Houtte, 2000). Effective monitoring and enforcement are imperative if mariculture expansion is to be sustainable in the future. However, monitoring and enforcement vary considerably among countries (Buschmann et al., 2009). Countries such as the U.S. (NMFS et al., 1997), Australia (NSW, 2012), Canada and the E.U. (Kristensen, 2000) have also adopted formal codes of conduct whose main objective is to promote the responsible development and management of aquaculture with appropriate sanctions.

The high correlation for individual species’ predicted HSI between mariculture location and natural occurrence suggests that mariculture farms are sensitive to changes in environmental conditions driven by climate change or other anthropogenic activities such as pollution (Parry et al., 2004; Easterling W. et al., 2007; Cheung et al., 2010; Merino et al., 2012; Cheung et al., 2015). Ocean warming may drive environmental conditions beyond the suitable range for various species and will cause thermal stress for a number of currently farmed species (e.g., cod, oysters). However, these rising temperatures may extend the growing season for some other species and may provide opportunities to farm new species or species that are currently economically marginal in the affected areas. Also, shellfish aquaculture is sensitive to ocean acidification (Ferreira et al., 2008; Evans et al., 2015; Clements and Chopin, 2016), as lower carbonate saturation state in the water can make it more difficult for calcifying invertebrates to produce shells. Carbon emissions may thus have a substantial impact on the distribution and diversity of potentially suitable farm sites for currently farmed species.
3.7 Conclusion

In this study, I identified a large global, environmentally suitable area for mariculture. Obviously, other non-environmental factors such as technological, economic and social constraints play a fundamental role in determining mariculture production in these regions. While this study approach is useful in defining areas on a broad scale, more detailed studies on the ‘ecological suitability’ (i.e., in terms of carrying capacity) will be required to further constraint the prediction of suitable area for mariculture development. Also, these currently suitable areas might transition to being unsuitable in the future due to human activities such as pollution, coastal zone activities, and climate change. Future studies should include other human uses of marine areas, e.g. ship routes, wind farms etc. and their potential competition with mariculture to further characterise the suitable areas for farming. Moreover, given the importance of seaweed farming in various regions, future studies should also collate data and information about seaweed mariculture locations and extend all analyses to seaweed. It will also be important to investigate and address the main constraints in sustainable mariculture development to help develop pathways that ensure the continued contribution of mariculture to global seafood production.
Chapter 4: Projecting global mariculture diversity under climate change

4.1 Introduction

The world population will reach an estimated 9 -10 billion by 2050, increasing global food demand by 70-100% (Baulcombe et al., 2009; De Silva and Soto, 2009; Alexandratos, 2012; Kapetsky et al., 2013a). Meeting global food demand - and doing so in a way that limits environmental damage - is a fundamental challenge to sustainable development (UN, 2013). Between 2011 and 2015, marine fisheries and mariculture (both marine and brackish aquaculture) produced an average of 106 million tonnes of seafood annually. Seafood contributes about 20% of protein intake for approximately 3.2 billion people in the world (FAO, 2018). Compared to animal production on land, seafood is generally considered to have a lower environmental impact (Hilborn et al., 2018; Hallström et al., 2019) - yet the role of seafood in achieving the sustainable development goals remains under-recognised and undervalued (HLPE, 2014). As a food high in protein and low in 'bad' fats, seafood provides a range of positive health benefits. Seafood consumption is recommended in most dietary guidelines (Meyer et al., 2003; Hallström et al., 2019) mainly because finfish and shellfish are an essential source of highly bioavailable vitamins, minerals and omega-3 (n-3) and omega-6 (n-6) polyunsaturated fatty acids (PUFAs). The latter is essential notably for cardiovascular health, cognitive function and prenatal and postnatal brain development.

Aquaculture has played an essential role in filling the gap between food fish demand and supply from capture fisheries. Global production of food fish from aquaculture (freshwater, marine and brackish) has increased from 2.6 million in 1970 to nearly half of the 171 million tonnes of food fish (excluding aquatic plants) consumed worldwide in 2016 (FAO, 2018), with Asia
continuing to dominate the sector and accounting for more than 92% of global aquaculture production (Phillips and Pérez-Ramírez, 2017). As part of this trend, the share of mariculture (including brackish production) has increased from 14% in 2000 to 37% in 2016 (FAO, 2018). Mariculture is a form of aquaculture where “farming of aquatic organisms in which the end product takes place in seawater, such as fjords, inshore and open waters, and inland seas or inland facility (RAS) in which the salinity exceeds 20 PSU” (FAO, 2004). The Sea Around Us mariculture database (www.searoundus.org) provides an estimate of an increase in mariculture production from 5 million tonnes in 1990 to 21 million tonnes in 2010. This increase is primarily driven by the growing demand for seafood derived from marine and brackish waters in developed countries (Campbell and Pauly, 2013; FAO, 2014), which focuses on high value omnivorous and carnivorous species (FAO, 2014). Although projections of the future contribution of aquaculture – including mariculture – to food supply is uncertain, it has been estimated that if all production inputs were available, the sector could provide 16 – 47 million additional tonnes of fish by 2030 (Hall et al., 2011). While aquaculture may increase food provision; it is important to note that recent work shows that from a nutritional perspective, wild-caught fish may provide a greater contribution to micronutrient intakes than common aquaculture species (Bogard et al., 2015).

Yet, climate change could reduce the anticipated potential seafood supply from mariculture. Sea level rise, increases in water temperature, ocean acidity, storm frequencies and wave action, as well as changes in salinity, among others, are expected to impact the suitability of marine habitats (coastal waters and open ocean) to farm seafood (Harley et al., 2006; Barange and Perry, 2009; Cheung et al., 2009; Gattuso et al., 2015). Increases in temperature and acidity, in particular, are also expected to directly affect the physiology and ecology of farmed species (Cochrane et al., 2009) by altering growth rates, disease susceptibility, survival rates, reproduction and shell quality.
in the case of bivalves (Handisyde et al., 2006). Such environmental changes might lead to a reduction in suitable farmed areas and redistribution of farmed species from their historical farming region particularly for species that are cultured using open or semi-open production systems, including salmon. Thus, climate change is expected to affect the quantity and quality of seafood from mariculture. Two studies have estimated the areas currently not utilised, but potentially suitable for mariculture, which could increase seafood production to contribute to and improve food security in the future (Gentry et al., 2017; Oyinlola et al., 2018). However, such suitable marine areas may be impacted under climate change, thereby reducing the chances of mariculture expansion and associated projected production in the future.

Recent studies that investigated climate change effects on the growth potential and availability of suitable marine areas for mariculture (Klinger et al., 2017; Froehlich et al., 2018) suggest that climate change impact will be heterogeneous across species and regions. Noticeable adverse effects are projected for aquaculture-suitable marine areas around the equator with substantial gains towards the poles. Selective breeding (Klinger et al., 2017) and changes to alternate farm species with favourable growth rates and market acceptability (Harvey et al., 2016) have been suggested as potential adaptation strategies that could be important to increase seafood production from mariculture under climate change.

To date, climate change impacts on mariculture richness or diversity remain poorly understood (Oyinlola et al., 2018). Here, mariculture richness is understood to represent the total number of species taxa that could be farmed in a given area – given environmental conditions and associated species preferences. Richness is one of the major components of the aquaculture species diversification (Harvey et al., 2016). Species distribution models (SDMs) are statistical tools that link species distribution occurrences in time and space with environmental data - and can,
therefore, be used to predict species occurrences based on environmental parameter sets (Guisan and Zimmermann, 2000b; Elith and Leathwick, 2009). Generally, SDMs generate a statistical or non-parametric relationship between environmental conditions such as temperature, oxygen, salinity, pH and other ocean variables with species’ occurrences, which are then used to define their potential fundamental niche (Hutchinson, 1959). The models ultimately predict an index of habitat suitability for the species around the niche (Elith and Leathwick, 2009). These tools have been widely used to assess past, current and future distributions of terrestrial (Polce et al., 2013; Newbold, 2018) and marine species (Cheung et al., 2010; Jones and Cheung, 2014; Cheung et al., 2015) as well as to quantify the potential suitable marine areas for mariculture (Oyinlola et al., 2018).

In this study, I quantify global patterns of mariculture richness for 85 of the currently most commonly farmed marine species in coastal and/or open ocean areas and project future trends and patterns under climate change. Specifically, I estimated a ‘mariculture diversity index’ for each species and how these would change by the middle and end of the 21st century under strong mitigation and business as usual scenario using an ensemble model approach with three Earth system models (ESMs) and three species distribution models (SDMs). I then discuss the implications of the findings for future seafood production and the environmental and social-economic opportunities and challenges of climate-adaptation for the mariculture sector.

4.2 Materials and methods
The method applied in this study includes five main steps. First, I quantified the historical mean ocean conditions (average of 1970-2000) suitable for farming aquatic organisms and estimated the environmental niche of 85 of the most commonly farmed species (Table S1). I then projected their habitat suitability index (HSI) over the global ocean based on average historical
environmental conditions. The future habitat suitability index for mariculture for each of the 85 currently most commonly farmed species under future scenarios of ocean conditions were then determined using three Earth System Models (ESMs). I then calculated the changes in mariculture diversity based on the model projections and used the averaged outputs (average across ESM models by spatial cell) to assess the impacts of climate change on mariculture. Lastly, associated model uncertainties were quantified. Each step is unpacked in further detail below.

4.2.1 Occurrence data

I obtained occurrence records of mariculture farm locations within countries' exclusive economic zones (EEZ) for 85 of the most commonly farmed marine species from the georeferenced mariculture database developed and described in chapter 3. All species’ farm location records were converted to a binary of presence or absence and rasterised on a regular spatial grid of 0.5° latitude x 0.5° longitude over the global ocean.

I then focused on these species because of their high economic and nutritional importance. Together, these species accounted for about 70% of all mariculture production out of 307 taxa farmed globally in 2015 (Chapter 2). These 85 species also met the minimum occurrence data requirements of more than seven sub-national units for SDMs (Elith et al., 2006), that in turn allow greater model accuracy when projecting future changes. These species included 55 chordates and 30 molluscs.
### 4.2.2 Environmental data

Datasets of eight environmental parameters were assembled; these include sea surface temperature, dissolved oxygen concentration, chlorophyll-*a* concentration, salinity, pH, silicate concentration, current velocity, and euphotic depth. 10-year averaged ocean current velocity data (1992-2002) was obtained from Estimating the Circulation and Climate of the Ocean (ECCO) Project (http://www.ecco-group.org). Values for temperature, pH, dissolved oxygen concentration, salinity, silicate concentration and chlorophyll-*a* concentration were gathered from three Earth system models (ESMs) that were part of the Coupled Models Inter-comparison Project Phase 5 (CMIP5): (1) the Geophysical Fluid Dynamics Laboratory Earth System Model 2M (GFDLESM2M); (2) the Institute Pierre Simon Laplace coupled model version 5 (IPSL) (IPSL-CM5-MR); and (3) the Max Planck Institute for Meteorology Earth System Model (MPI-ESM-MR) and averaged over the period 1970-2000 for each ESM. All environmental data were interpolated using bilinear methods (Legendre and Legendre, 1998) over the global ocean (189.75°W to 179.75°E and 89.75°N to 89.75°S) on a regular spatial grid of 0.5° latitude x 0.5° longitude (the same as occurrence rasterized data) and for two vertical layers: surface (0-10m) and sea bottom depth, where available.

### 4.2.3 Habitat suitability index

I used a multi-species distribution model (SDM) approach to determine areas that would be considered as suitable for farming the 85 selected species. First, the coordinates of the rasterized farm location data and environmental data were harmonised on a regular spatial grid of 0.5° x 0.5° and determined the environmental quality parameters that best explain the occurrences of farming locations using the eigenvalue diagram (Chapter 3) implemented in the Ecological Niche Factor Analysis (ENFA) (Basille et al., 2008). I then computed current mariculture richness using three
SDMs: Gradient Boosting Machine (GBM) (Friedman, 2002; Ayyadevara, 2018), Surface Range Envelope (SRE) (Busby, 1991) and Maximum Entropy (MAXENT) (Phillips et al., 2006). Next, I applied each model to estimate the habitat suitability index (HSI) of each species for each gridded cell of the ocean (i.e. 0.5º x 0.5º). The HSI scales from 0 to 1 (low to high) to indicate the environmental suitability of the selected environmental conditions for each species in each spatial cell.

**4.2.4 Present suitable areas for mariculture**

I identified an area as potentially suitable for mariculture based on the SDMs results, and a set of additional environmental and socio-economic constraints. First, by comparing the predicted HSI with current gridded farm location data, the minimum HSI above which mariculture can potentially occur was determined. The thresholds were identified at the species level by quantifying a species' 'prevalence', i.e., the fraction of cells in which the species is present (Phillips et al., 2009). I set the known farm locations' HSI as 'presence' and the locations with suitable HSI but no farms as 'absence' and evaluated 'prevalence' using the evaluate function in the R dismo package (Hijmans et al., 2017). The predictive values of habitat suitability for mariculture below the prevalence value were assigned 0 and predicted HSI values higher than the prevalence value was assigned 1 (Chapter 3). Second, I assumed that farm operations would not extend beyond a country's Exclusive Economic Zone (EEZ) (Chapter 3). Third, I assumed that mariculture activities would be restricted by currents and only included spatial cells with a current velocity between 10 cm s\(^{-1}\) and 100 cm s\(^{-1}\) (Kapetsky et al., 2013). Lastly, as most marine protected areas (MPAs) do not allow aquaculture, existing MPAs, as documented in the Atlas of Marine Protection
(http://www.mpatlas.org/), were not considered as suitable areas for future marine aquaculture activities (Table 4.1).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Justification</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat Suitability Index above the occurrence threshold</td>
<td>Exclude area with environmental conditions that are not suitable for the growth and survival of the farmed species</td>
<td>“Prevalence (pv)” the fraction of cells at which the species is present (Phillips et al., 2009). HSI = 1, if HSI ≥ pv HSI = 0, if HSI &lt; pv</td>
</tr>
<tr>
<td>Within the exclusive economic zone</td>
<td>Political boundary</td>
<td>200 nm (370.4 km)</td>
</tr>
<tr>
<td>Within a range of ocean current velocities</td>
<td>Mariculture operations avoid disturbance from strong ocean currents</td>
<td>Current velocity between 10 cm s⁻¹ and 100 cm s⁻¹ (Kapetsky et al., 2013)</td>
</tr>
<tr>
<td>Outside of designated marine protected areas</td>
<td>Most MPAs do not allow aquaculture operations within their boundaries</td>
<td>Exclude designated marine protected areas</td>
</tr>
</tbody>
</table>

4.2.5 Model testing

The robustness of the SDM outputs was tested by comparing the predicted HSI with reference records of species occurrences. The model was run with 75% of all records as a training dataset to develop each SDM and calculate each species’ HSI. The remaining 25% of the data were used for model evaluation. The Area Under the Receiver Operating Characteristic Curve (AUC) for each set of model predictions was calculated using the ROCR package in R (Sing et al., 2007). AUC values range from 0 to 1, with 0.5 indicating that the model is no better than a random sample of values, and 1 indicating that the model has high predictive power. The individual species model was then used as weighting values for the multi-model ensemble (Jones and Cheung, 2015).
4.2.6 Projection of future suitability index

Model projections for the future suitability of the ocean for farming of the 85 species included in this study under climate change were run using outputs from three Earth system models (ESMs) in CMIP5: GFDL-ESM-2M; IPSL-CM5-MR and MPI-ESM-MR. Two climate change scenarios were considered: Representative Concentration Pathway (RCP) 2.6 and RCP 8.5, representing the low (‘strong mitigation’) and high (‘business-as-usual’) greenhouse gas emission scenarios, respectively. I present the individual ESM output and the multi-model output (average across ESM models by spatial cell).

4.2.7 Analysis

The global pattern of change in mariculture richness from 1995 to 2100 was analysed under the two climate change scenarios. I estimated the mariculture richness in each 0.5° x 0.5° cell and then calculated the total number of species that could be farmed in each EEZ for the 85 selected species for each year from 1995 to 2100. I then estimated the percentage change in mariculture richness between the 2005s (i.e., an average of 1995 to 2015), the 2050s (i.e., an average of 2040 to 2060) and the 2090s (i.e., an average of 2080 to 2100). Using model outputs, I discuss the potential opportunities and challenges for the future sustainable development of global mariculture. All models and analyses were run using the statistical programming software R (R Core Team, 2018) and maps were made in Matlab (MATLAB and Statistics Toolbox 2018a).
4.3 Results

4.3.1 Model evaluation

All three models estimate distributions of mariculture richness that were strongly supported by observations, as indicated by the high AUC model values (Figure 4.1). The AUC values varied among ESMs and SDMs, with the 25th and 75th percentiles of Surface Range Envelope (SRE) (Average AUC across all ESM models) predictions having AUC values of 0.76 and 0.91 across models, respectively (an AUC value of 0.5 indicates that a model’s prediction is no better than random choice). Maximum Entropy (MAXENT) and Gradient Boosting Machine (GBM) had the highest AUC values; with both scoring AUC values of 0.91 and 0.95 for the 25th and 75th percentiles, respectively. The 25th and 75th percentiles of the estimated prevalence value for each species (i.e., the HSI threshold below which the marine area was considered unsuitable for culturing the specific modelled species) ranged from 0.32 to 0.65.

Figure 4.1. Prediction evaluation of each SDM used in the analysis. AUC for the habitat suitability index (HSI) of 85 most commonly farmed species across Earth System Model and Species Distribution Model. The box represents the interquartile range of AUC scores; the horizontal lines in the boxplot represent median values, and the upper and lower whiskers represent scores outside the middle 25th and 75th percentiles.
4.3.2 Current mariculture richness and potential suitable marine area for mariculture

The model predicted the current pattern of mariculture richness across all models for the reference time (2005s, average from 1995-2015) under the strong mitigation RCP 2.6 and high emission RCP 8.5 (Figure 4.2a). Results show similar trends under both scenarios. Mariculture richness was highest in North subtropics (66.5°N and 35.5°N) (Figure 4.2b), particularly, the East China Sea (species richness = 25 – 53 among RCP scenarios) and North of the Gulf of Mexico (species richness = 15 – 45 among RCP scenarios). While lowest mariculture richness is at the North Frigid Zone (i.e. Arctic) (90°N and 66.5°N). Other noticeable area of richness includes, the southwestern Atlantic coast (species richness = 30 – 45 among RCP scenarios) and West Africa (species richness = 35 – 40 among RCP scenarios), the Yellow Sea (species richness = 30 – 50 among RCP scenarios) and the Caribbean Sea (species richness = 20 – 40 among RCP scenarios).

Also, under both scenarios (RCP 2.6 and 8.5) in the current time (the 2005s), I estimated a total 113 million km² suitable marine area for mariculture for all the 85 species in this analysis (Figure 4.3). The highest prediction was estimated for tropics with 66 million km² suitable area while the Arctic has the lowest area of 7.8 million km². Total suitable area for Finfish was estimated to be 83 million km² and for molluscs 49 million km².
Figure 4.2. Predicted global distribution and range of mariculture species richness for the reference period (1995-2015) for 85 species of finfish and molluscs under RCP 8.5 (a) on 0.5° by 0.5° grid cells, and (b) by latitude. Boxes in (b) represent the interquartile range of number of species; the horizontal lines in the boxplot represent median values, and the upper and lower whiskers represent scores outside the interquartile range. All results presented as a multi-model ensemble. Arctic circle (90°N and 66.5°N), North temperate (66.5°N and 35.5°N), North subtropics (35.3°N and 23.5°N), Tropics (23.5°N and 23.5°S), South subtropics (23.5°S and 35.5°S) and South temperate (35.5°S and 66.5°S).
Figure 4. 3. Regional predicted potential suitable mariculture area for 85 species for the present (2005s, average from 1995-2015), 2050s (average from 2040-2060) and 2090s (average from 2080-2100) under (a) RCP 2.6 (b) RCP 8.5. Arctic circle (90°N and 66.5°N), North temperate (66.5°N and 35.5°N), North subtropics (35.3°N and 23.5°N), Tropics (23.5°N and 23.5°S), South subtropics (23.5°S and 35.5°S) and South temperate (35.5°S and 66.5°S).
4.3.3 Climate change induced impacts on mariculture richness and suitable mariculture areas

Relative to current (1995-2015) mariculture species richness, projected future mariculture species richness only changed slightly globally. Under RCP 2.6, the model ensemble projected an increase in mariculture species richness of 1.02% ± 0.59 (standard error) by the 2050s (average from 2040-2060) and 3.35% ± 0.62 by the 2090s (average from 2080-2100) (Table 2, Figure 4.4a, Figure 4.5). A decrease of 0.49% ±0.11 was projected by the 2050s and an increase of 2.39% ±0.53 by the 2090s under RCP 8.5 (Table 4.2, Figure 4.4b).

Table 4.2. Percentage change in global mariculture species richness by mid-century (average from 2040-2060) and end of the century (average from 2080-2100) relative to the 2005s (average from 1995-2015) under RCP 2.6 and 8.5 scenarios. GFDL = Geophysical Fluid Dynamics Laboratory Earth System Model 2; IPSL = Institute Pierre Simon Laplace; MPI = Max Planck Institute for Meteorology Earth System Model. The error limits represent the standard deviation across Earth System Models.

<table>
<thead>
<tr>
<th>Model uncertainty</th>
<th>% Change in mariculture species richness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GFDL</td>
</tr>
<tr>
<td></td>
<td>2050s</td>
</tr>
<tr>
<td>RCP 2.6 (Global)</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td>±0.59</td>
</tr>
<tr>
<td>RCP 8.5 (Global)</td>
<td>-0.64</td>
</tr>
<tr>
<td></td>
<td>±0.11</td>
</tr>
</tbody>
</table>
Figure 4.4. Impacts of climate change on global mariculture species richness for 85 of the currently most commonly farmed species by the 2050s (average 2040-2060) relative to the 2005s (average 1995-2015). The black line in the ocean represents the boundary of Exclusive Economic Zones (Sea Around Us (www.searoundus.org) Percentage changes under (a) RCP 2.6 and (b) RCP 8.5. Warm colours represent losses while cool colours represent gains.
Figure 4.5. Impacts of climate change on global mariculture species richness for the 85 most common currently farmed species by the 2050s (average from 2040-2060) relative to the 2005s (average from 1995-2015).
Projected changes in mariculture species richness under climate change varied across latitudes (Figures 4.6a and b). The latitudinal average was projected to shift toward the poles (i.e., South and North) under the two RCP scenarios. Under RCP 8.5 scenario, mariculture species richness in the tropics was found to decline by 10.1% ±25.7 (standard deviation) by the 2050s relative to the 2005s, compared to a decline of 2.2% ± 21.1 under RCP 2.6 over the same time frame. A substantial increase of about 41.1% ±42.2 was observed between 90ºN and 66.5ºN under RCP 8.5 compared to 19.7% ±47.1 under RCP 2.6, for the same period.
Figure 4. 6. Latitudinal average of the mean percentage changes in mariculture species richness in the 2050s compared to the 2005s under (a) RCP 2.6 and (b) RCP 8.5. Boxes represent the interquartile range of per cent changes; the horizontal lines in the boxplot represent median values, and the upper and lower whiskers represent scores outside the interquartile range. All results presented as a multi-model ensemble. Arctic circle (90°N and 66.5°N), North temperate (66.5°N and 35.5°N), North subtropics (35.3°N and 23.5°N), Tropics (23.5°N and 23.5°S), South subtropics (23.5°S and 35.5°S) and South temperate (35.5°S and 66.5°S).
Under RCP 2.6, the model ensemble projected a decrease in the suitable marine area for mariculture of 1.4% ± 0.3 (standard deviation) by the 2050s and 1.20% ± 0.26 by the 2090s (Figure 4.3a). A decrease of 2.0% ±0.5 and 3.7 % ±0.59 was projected by the 2050s and 2090s, respectively, under the RCP 8.5 scenario (Figure 4.3b). Similarly, global potential suitable mariculture area was projected to decline by 2% ±0.9 under RCP 2.6, and by 2.8% ±0.7 under RCP 8.5 by the 2050s (Figure 4.7). For molluscs, the total marine area potentially suitable for mariculture declined by 5.3%±3.3 and 6.4% ±3.3 under RCP 2.6 and 8.5, respectively (Figure 4.8).

Figure 4. 7. Regional predicted potential mariculture area for finfish for the present (2005s, average from 1995-2015), 2050s (average from 2040-2060) and 2090s (average from 2080-2100) under (a) RCP 2.6 (b) RCP 8.5.
Figure 4. 8. Regional predicted potential mariculture area for molluscs for the present (2005s, average from 1995-2015), 2050s (average from 2040-2060) and 2090s (average from 2080-2100) under (a) RCP 2.6 (b) RCP 8.5.
4.3.4 Projected climate change impacts on the exclusive economic zones (EEZs) with existing mariculture industry

Globally, the exclusive economic zones (EEZs) that currently have farm operations were projected to lose 1.3% ±0.5 and 5.0% ±0.1 in mariculture species richness under RCP 2.6 and RCP 8.5, respectively, by mid-century relative to the 2000s period (Table 4.3). These projections focused on EEZs where mariculture facilities are currently known to operate and where there is a historical record of farming a given species. Specifically, mariculture species richness was projected to decline in about 62% of EEZs worldwide. Many countries with established mariculture operations since 1950 were projected to lose a substantial cultured marine species due to unsuitable ocean parameters by the middle of the century under both RCP 2.6 and RCP 8.5 (Figure 4.9a and b). The model projected declines between 20% and 100% in currently utilised EEZs by mid-century relative to the 2005s under both RCP 2.6 and 8.5 scenarios, respectively, in EEZs of the Pacific and Western Indian Ocean Small Island States and Territories, as well as Indonesia, Russia, Chile and Ecuador. Large declines (30%-70%) were also projected for Canada (Pacific coast) (median 56.57%) Southern Chile (median -39.54%), Senegal (median 45.29%) and the Philippines (median 63.87%).

Specifically, Canada (Pacific coast), Southern Chile and the Philippines were projected to lose in finfish mariculture species richness (Figure 4.10a). However, the model projected a slight increase in molluscs’ mariculture species richness (Figure 4.10b). Under RCP 8.5, moderate levels of decline (approximately 20%) were projected for the Caribbean Sea, and waters around Europe, Morocco, Japan and Australia. Increases in currently utilised EEZs for selected farmed species were projected for Newfoundland and Labrador (60%-70%), parts of Argentina’s EEZ (10%-
20%), around India (20%-80%), around Turkey and Greece (5% - 20%), Natal- Brazil (10%-60%) and the Northern Philippines Sea (20%-100%).

Table 4.3. Percentage change in EEZs with currently established mariculture operations for select species by mid-century (average from 2040-2060) and end of the century (average from 2080-2100) relative to the 2005s (average from 1995-2015) under RCP 2.6 and 8.5 scenarios. The error represents standard error of projections across different Earth system models.

<table>
<thead>
<tr>
<th></th>
<th>% Change in mariculture species richness</th>
<th>GFDL 2050s</th>
<th>GFDL 2090s</th>
<th>IPSL 2050s</th>
<th>IPSL 2090s</th>
<th>MPI 2050s</th>
<th>MPI 2090s</th>
<th>Multi-model 2050s</th>
<th>Multi-model 2090s</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP 2.6 (Global)</td>
<td></td>
<td>-1.79</td>
<td>-2.15</td>
<td>-1.79</td>
<td>-2.15</td>
<td>-0.19</td>
<td>-1.48</td>
<td>-1.26 ±0.54</td>
<td>-1.35 ±0.5</td>
</tr>
<tr>
<td>RCP 8.5 (Global)</td>
<td></td>
<td>-4.93</td>
<td>-6.54</td>
<td>-5.21</td>
<td>-10.51</td>
<td>-4.83</td>
<td>-6.96</td>
<td>-4.99 ±0.12</td>
<td>-8.00 ±1.26</td>
</tr>
</tbody>
</table>

Other countries had projected declines in mariculture species richness with a median value of 27.5% (25th to 75th percentiles = -6.7% – -52.2%) across models by 2050s under both RCPs. These included Caribbean countries (40% to 80%), Norway (20% to 40%), Ecuador (20% to 80%), Southern Chile (20% to 100%), Southern Philippines (20% to 80%) and Malaysia (20% to 60%). Gains in mariculture richness were projected for some countries including Norway (offshore) (20% to 40%) and the Philippines (20% to 60%) under RCP 2.6 and Colombia (20%), Northern Chile (60% to 80%), Sweden (20% to 80%), Northern Philippines (20% to 80%) and Russia (North Pacific Ocean) (40% to 100%) under RCP 8.5. Under both scenarios, Canada (Newfoundland and Labrador) (20% to 100%), India (60% to 100%), New Zealand (20 to 60%) and Australia (Spencer Gulf) (60% to 80%) were projected to make substantial gains in mariculture species richness.
Figure 4.9. Impacts of climate change on mariculture species richness for 85 of the currently most farmed species, limited to countries presently practising mariculture for selected species, by mid-century (average 2041-2060) relative to 2005s (average 1995-2015). Percentage changes under (a) RCP 2.6 and (b) RCP 8.5. Warm colours represent losses while cool colours represent gains.
Figure 4. 10. Projected impact of climate change on finfish and mollusc mariculture species richness for the exclusive economic zones with present mariculture activities. (a-b) finfish mariculture species richness under RCP 2.6 and 8.5, (c-d) molluscs mariculture species richness under RCP 2.6 and 8.5.
4.3.5 Impact of climate change on important mariculture species

Although the impact on climate change on potentially suitable mariculture areas for the 85 species studied in this paper was projected to be small, some farmed species were projected to be particularly impacted by climate change (Figure 4.11, Figure 4.12 for map). By the mid-21st century, Australia and Canada's Pacific coast, for example, were projected to lose about 32% and 84%, respectively, of suitable marine area for farming Atlantic salmon (Figure 4.11a) under RCP 2.6 while the loss was projected to be 60% for both areas under RCP 8.5. In contrast, for the same timeframe, the area suitable for farming Atlantic salmon in Norway was projected to increase by about 29% and 48% under RCP 2.6 and 8.5 respectively and by 100% under both scenarios for Sweden (Figure 4.11a).

The models consistently projected that cobia (*Rachycentron canadum*) farming in Panama would be strongly impacted under RCP 8.5, with a near-total loss in suitable area (Figure 4.11b). In contrast, under RCP 2.6, the country was projected to gain close to 21% more suitable marine area for culturing cobia. Suitable area for European seabass (*Dicentrarchus labrax*) farming was projected to increase in Greece (3%), France (Atlantic) (7%) and Malta (10%) under RCP 2.6; however, declines were projected under RCP 8.5 for Greece (2%) and France (Atlantic) (21%), while findings showed Malta would gain (23%) suitable marine areas by mid-century relative to the 2005s (Figure 4.11c). In total, 19 EEZs were projected to gain more suitable area for the farming of Pacific cupped oyster (*Crassostrea gigas*) under RCP 2.6, with highest gains in New Caledonia (42%), the West coast of the USA (34%) and the Subarctic region around Alaska (32%). Under RCP 8.5, we projected 15 EEZs to gain suitable area for the same species (Figure 4.11d). Subarctic Alaska, Morocco and the West coast of Canada registering the highest gains at 83%,
55% and 46% respectively. New Caledonia, France and Italy, on the other hand, were projected to face losses of 100%, 67% and 58% respectively under RCP 8.5.
Figure 4.11. Percentage changes in potential suitable mariculture area for countries currently farming selected species by the middle of the century (average from 2040-2060) relative to 2005s (average from 1995-2015) under RCP 2.6 and 8.5. a) Atlantic salmon; b) Cobia; c) European bass; d) Pacific cupped oyster.
Figure 4. Impacts of climate change on global suitable marine areas for mariculture for currently farmed species by the 2050s (average 2040-2060) relative to 2005s (average 1995-2015). The black line in the ocean represents the boundary of Exclusive Economic Zones (Sea Around Us (www.searoundus.org) Percentage changes under RCP 2.6 (Maps on the left) and RCP 8.5 (Maps on the right) a) Atlantic salmon b) Cobia c) European bass d) Pacific cupped oyster.
4.4 Discussion

In recent years, the growth of global mariculture production has helped maintain a relatively stable seafood supply in the world (Campbell and Pauly, 2013; FAO, 2018), with aquaculture being considered the fastest-growing food system in the world (FAO, 2018). However, the study findings highlight the uncertainties associated with the future development of global mariculture (both marine and brackish aquaculture). I projected a large-scale redistribution of mariculture species diversity and changes in potential areas suitable for mariculture in the world’s oceans. Specifically, under climate change, the assembled model developed in the study projected gains in mariculture species richness at higher latitudes, and losses throughout much of the tropics, in line with previous findings (Handisyde et al., 2006; Porter et al., 2014).

Species diversification has been identified as an essential strategy toward increasing food supply from aquaculture: a necessary action to improve the aquaculture food sector's profitability and flexibility (Harvey et al., 2016). Some studies (Le François et al., 2010; Harvey et al., 2016) have argued that species diversification could lend sector resilience, particularly under climate change. These results clearly highlight that such species diversification would need to consider the projected impacts of climate change on the diversity of species that can be farmed, particularly in the tropics that currently boast high species richness, but stand to register the greatest losses under climate change. Such care in potential future species diversification is all the more needed, given the sector’s contribution to nutrition and food security (Thilsted et al., 2016), especially given projected declines in capture fisheries under climate change (Cheung et al., 2010).

Although the study projected that future Arctic ocean conditions would be suitable for mariculture operations, and could see an increase in mariculture species richness, this region is
unlikely to support mariculture development from a conservation and governance perspective. While mariculture operations in the Arctic region contributed about 2% of total world aquaculture production in 2015 (Troell et al., 2017a), Arctic ocean ecosystems are generally considered sensitive to human activities (Meier et al., 2014; Riedel, 2014). Thus, the expansion of mariculture activities in the Arctic would conceivably have a considerable impact on marine biodiversity and ecosystem functions. Such impacts would be exacerbated if the development of operations were to take place in the absence of effective environmental management and regulations, resulting in ecological impacts through, for example, excessive nutrient and chemical outflows from the farms (Ivanov et al., 2013), escapes of farmed fish (Jensen et al., 2013), as well as the risk of disease and parasite transfer from farmed to wild stocks (Palm, 2011). Opening the Arctic region to aquaculture activities may also further exacerbate the region’s vulnerability to climate change.

The important losses in marine diversity and potential suitable area for mariculture projected under RCP 2.6 and RCP 8.5 for tropical regions underscore the considerable threat that climate change presents to areas that currently contribute a substantial amount to food fish production and that also depend on a large proportion of that production for local food security, income and employment (FAO, 2018). Aquaculture is viewed as critical to supporting food security throughout developing tropical countries due to the static or declining contributions by capture fisheries to the food fish basket (Brummett et al., 2008). However, mariculture may not be the panacea to nutritional security, particularly for developing countries, it is made to be (Golden et al., 2016; Bogard et al., 2017). These findings underline the importance of this uncertainty. In addition, for countries where mariculture has been an important part of the coastal economy (e.g., China), if the loss in potentially suitable mariculture area were to translate into a reduction in
growth performance and subsequent reduction in aquaculture production output, this could be detrimental to the sustainable development of these coastal communities (Singh et al., 2018).

This study results further lend credence to previous findings pointing out that changes in ocean conditions because of climate change would affect the suitable environmental area that supports the farming of aquatic species in open water farming systems (Klinger et al., 2017; Froehlich et al., 2018; Oyinlola et al., 2018). Mariculture species perform best within a stress-free environment. Hence, to optimise production and be most cost-effective, farmers strive to locate ocean-based facilities within the optimal oceanic environment for the farmed species (Benetti et al., 2010). In this study, I determined the best combination of oceanic parameters to achieve optimal growth conditions for each of the 85 currently most commonly farmed species (Basille et al., 2008; Oyinlola et al., 2018) using three different models. Such quantitative methods and models represent a useful tool to inform the aquaculture sector of the possible risks and likely vulnerabilities of their current and planned operations under climate change.

While this study focused specifically on the effects of climate change on the environmental suitability for mariculture species, there are a number of other direct and indirect impacts of climate change on mariculture that may render the future viability and sustainability of mariculture production uncertain. Body size of finfish is expected to decline for open water systems due to increases in temperature limiting oxygen for optimal growth (Pauly and Cheung, 2017). Higher temperatures could also exacerbate the prevalence of aquaculture related diseases and parasitic infections (Walker and Mohan, 2009; Karvonen et al., 2010) resulting in economic losses, in addition to estimated losses in potentially suitable mariculture areas. Simulations indicate that climate change will negatively impact the abundance and maximum catch potential of forage fish from capture fisheries (Cheung et al., 2010; Cheung et al., 2016) leading to a possible reduction in
fishmeal and fish oil supply, which will affect aqua-feed production. Substantial declines in agricultural yields have been projected to occur in most regions of the world (Nelson et al., 2009; Piao et al., 2010; Schlenker and Lobell, 2010), further impacting the supply of (plant source in) aquafeeds. Future growth and production scales also will be shaped by a number of indirect socioeconomic factors such as population, technology and consumption patterns. Future studies should focus on how these may impact mariculture production in the future.

The approach of integrating three models to simulate changes in the suitable marine area available for farming and mariculture species richness enables us to explore the structural uncertainty of projected species distributions based on their environment (Cheung et al., 2016). GBM and MAXENT had the highest AUC values. In the case of GBM, this may be due to the model’s ability to build some regression trees sequentially from pseudo-residuals by least-squares at each iteration (Friedman, 2002). This attribute helps GBM correct errors made by previously trained regression trees. In GBM, a ‘tree’ is made up of random sub-samples of the dataset incrementally improving the model (Moisen et al., 2006). With MAXENT, the model provides the user with the ability to weight input variables (Jones and Cheung, 2015), thereby preventing over-fitting of the model by determining how much the likelihood should be penalised. Likelihood penalisation is necessary to control model complexity and the variance of the estimated suitability index (Murphy, 2012; Hutchinson et al., 2015).

These results underscore that future climate change impacts will impact some regions more strongly than others, and can help inform actions required to mitigate and adapt to the effects of climate change on the future suitability of ocean sites for farming aquatic organisms for food production. While the findings clearly highlight that future changes in the marine environment will significantly impact mariculture activities, extreme events and their likelihood to increase in
severity and frequency will also need to be given due consideration. Similarly, proximity to markets, conflicts with other oceans users and availability of local aquafeed ingredients will continue to be important determinants of aquaculture species diversification and production (Klinger and Naylor, 2012). Integration of these considerations together with a review of marine aquaculture zoning and site selection factoring in climate change will be needed to improve the adaptive capacity of the sector, contribute to reducing uncertainties and minimise impacts on production and dependent socio-economics of mariculture countries. Also, hybridisation and development of new species strains that have better survival rates at higher temperatures and lower oxygen levels should be encouraged through research and development. Future increases and improvements in cost-effective technology should also improve land-based operations. Lastly, it is important to consider that the sustainability of the future expansion of mariculture may, in part, be linked to the effectiveness of conservation and governance measures. Policymakers must set clear objectives for future mariculture sustainability efforts and ensure the rule of law and due process are followed and enforced.
Chapter 5. Projecting future seafood production from mariculture under climate change

5.1 Introduction

Sustainable seafood supply is facing multiple challenges in the present day, and these challenges might continue to the end of the century. With population growth and the improvement in societal wealth, demand for seafood is expected to continue to increase (Garcia and Rosenberg, 2010; FAO, 2018). However, marine fisheries catch has been stagnant since the 1990s as most fisheries resources are fully- or over-exploited (Delgado, 2003; Garcia and Rosenberg, 2010; FAO, 2018). While ocean warming has altered global fisheries catch potential of some fish stocks since the 1930s (Free et al., 2019). Particularly, global catch potential is projected to decrease by 3.1 million tonnes per degree Celsius of atmospheric warming (Cheung et al., 2016). Such decrease is particularly intense in the tropical oceans because the distribution ranges of tropical fish populations are projected to shift towards higher latitude. While seafood production from marine aquaculture (mariculture) expanded rapidly in the last few decades, it remained a small proportion of global seafood production (Campbell and Pauly, 2013). However, there is much anticipation that the contribution from mariculture would substantially increase in the future (FAO, 2018; Froehlich et al., 2018).

Climate change renders the future expansion of mariculture production uncertain. Previous studies reported projections of climate change impacts on seafood production from mariculture (Chapter 3, Froehlich et al., 2018), suggesting that climate change will reduce the suitable marine areas for mariculture (Chapter 3). Specifically, marine fishes and invertebrates have physiological optima and limits on ocean conditions such as oxygen, temperature, salinity and pH (Portner, 2010; Cheung et al., 2013). Understanding these biological optima and limits plays an essential role in
ensuring growth and reducing the mortality of farmed organisms in aquaculture operation (Benetti et al., 2010). Suitable and optimal environmental conditions of farmed species were approximated by estimating their habitat suitability index (HSI) (Chapter 2) that described the relationship between a species observed occurrences and their environmental conditions (Guisan and Zimmermann, 2000b; Hirzel et al., 2006). Applying the characterised relationship to future ocean conditions under climate change, total habitat suitability index for all the farmed species were projected to shift in distributions. Also, the area where mariculture is conducted at present-day would decrease (Chapter 4). Such results suggest a potential reduction in mariculture production. However, these modelling studies do not include indirect drivers of mariculture production, for instance, changes in fishmeal and fish oil supply or farm-gate price.

Most fish mariculture relies on fishmeal and fish oil (FMFO) as inputs into aquafeed. A larger amount of FMFO come from small pelagic forage fishes such as herring, anchovies, mackerel that are targeted by reduction fisheries and have an annual catch of about 20 million tonnes (Cashion et al., 2017). Aquaculture used about 68.2% of fishmeal and 88.5% of fish oil produced in the world in 2006 (Tacon and Metian, 2008). Even though there are currently increasing efforts towards the replacement of FMFO with plant-based protein source (Turchini et al., 2009; Torrecillas et al., 2017; Lazzarotto et al., 2018), the use of fishmeal rather than plant-based meal is still high in farmed marine finfish and crustacean species, particularly species with high trophic level (Boyd, 2015). Thus, the sustainability and growth of aquaculture currently rely on the continuous supply of forage fish for fish meal and fish oil. Climate change threatens the supply of forage fishes from capture fisheries, which may limit the future expansion of aquaculture (Shepherd and Jackson, 2013).
Seafood produced from mariculture is traded globally, and thus, its production is expected to be partly dependent on consumer demand, itself affected by the price of seafood products. Specifically, revenue from mariculture is highly reliant on the demand elasticity, which is responsive to change in the price of the commodity (Andreyeva et al., 2010). Climate change could cause a decline in the supply of seafood production from mariculture, which might impact the price of seafood that subsequently affects mariculture production.

In this study, I aim to develop a model to project future mariculture production potential by taking into account direct and indirect drivers including the suitable marine area for farming, total world fishmeal and fish oil production, seafood price and characteristics of the farm species such as trophic level. Here, mariculture production potential (MPP) is defined as the maximum amount of biomass of a species that could potentially be continuously produced from mariculture for decades in a particular area. I hypothesise that global MPP will decrease over the 21st century as a result of climate change impacts on the suitable marine areas for mariculture and fishmeal and fish oil production. I also examine the regional differences in projected changes in MPP under contrasting greenhouse gas emissions scenarios.

5.2 Methodology
5.2.1 Mariculture production and their direct and indirect drivers

I obtained mariculture production data by each EEZ per farmed species from the updated Sea Around Us Global Mariculture Database (GMD) (Chapter 2). The database contains annual mariculture production by taxa, countries and sub-national units (e.g., provinces, states). Also, I gathered the corresponding farm-gate price from the farm-gate price database (Chapter 2) and harmonised the two datasets by year, EEZ and farmed species.
The trophic level of each farmed species recorded in GMD (Chapter 2) for fishes was obtained from FishBase (http://www.fishbase.org) and invertebrates from SealifeBase (www.sealifebase.org) databases. There are differences in trophic level of the same species between samples obtained from the wild and in fish farms because of the differences in their diet composition and protein sources in different production systems. As there is no standard method for estimating trophic level in farmed species, the trophic levels reported in FishBase and SeaLifeBase used as best-available estimated. To ensure that each modelled species had the minimum number of occurrence records for robust species distribution model (SDM) prediction (Elith et al., 2006), I focused on modelling the distributions of farmed species that were farmed in at least seven sub-national units (i.e. provinces, states). Based on the GMD, I identified and subsequently focused on 85 farmed mariculture species (55 Chordata and 30 Mollusca) that met the above criteria. Crustaceans were excluded from this study because mariculture operations for crustaceans using open pens or tanks are limited relative to the large area of predicted suitable mariculture area for farming crustaceans (Chapter 3). Species biological information including trophic level, maximum and minimum occurrence depth, length-weight relationships, preferred biome and habitat were obtained from FishBase (http://www.fishbase.org/), SealifeBase (www.sealifebase.org) and the Encyclopaedia of life (http://eol.org/).

A list of marine species used in reduction fisheries was obtained from the database described by Cashion et al. (2017). The database is derived from the reconstructed fisheries landings (i.e. excluding discarded catch) by taxon for each fishing country/Exclusive Economic Zone (EEZ) for each year from 1950 to 2016 as documented in Pauly and Zeller (2016). The forage fishes’ names reported in the database were extracted, and the corresponding percentage by weight used in reduction fisheries for each year. Records that were not reported at the species level (i.e., with
genus and species specified) were excluded from this analysis. In total, I focused on 106 species in 174 EEZs that accounted for 78% of fishmeal and fish oil production in 2014.

I collected datasets for eight environmental parameters: sea surface temperature, dissolved oxygen concentration, chlorophyll-α concentration, salinity, pH, silicate concentration, current velocity, and euphotic depth. Ten years averaged ocean current velocity data (1992-2002) was obtained from Estimating the Circulation and Climate of the Ocean (ECCO) Project (http://www.ecco-group.org). Surface values for temperature, pH, dissolved oxygen concentration, salinity, silicate concentration and chlorophyll-α concentration were gathered from three Earth system models (ESMs) that were part of the Coupled Models Inter-comparison Project Phase 5 (CMIP5) (see Chapter 4 for details) and averaged over the period 1970-2000 for each ESM. All environmental data were interpolated using bilinear methods (Legendre and Legendre, 1998) over the global ocean (189.75 °W to 179.75 °E and 89.75 °N to 89.75 °S) on a regular spatial grid of 0.5° latitude x 0.5° longitude (the same as occurrence rasterized data) and for two vertical layers: surface (0-10m) and sea bottom depth, where available

5.2.2 Model structure and development

I developed and applied a four-step framework (Figure 5.1) to project MPP under different climate change scenarios. First, for each farmed species, I predicted the marine areas within the EEZ where it would be suitable for mariculture activities. I used species distribution models (SDMs) to quantify the ecological niche of each species for the present-day period (1970-2000) and calculated HSI for each 0.5° latitude by 0.5° longitude grid cell of the ocean (see Chapter 3). Secondly, I applied spatial filters that were informed by physical and social-economic constraints of mariculture location to generate potentially suitable area for mariculture. Thirdly, I applied
SDM to project future potential suitable area for mariculture under climate change (see Chapter 4). Finally, using a general additive model (GAM), an empirical relationship between the potentially suitable area for mariculture with species’ farm-gate price, predicted HSI for mariculture, fishmeal and fish oil potential production, and species’ trophic level to estimate the mariculture production potential was developed.
Figure 5.1. Schematic representation of the structure of the model used to project mariculture production potential.
5.2.2.1 **Species distribution modelling**

I obtained geo-referenced locations of 85 farmed mariculture species (55 Chordata and 30 Mollusca) as described in Chapter 2. Each species’ mariculture location record was converted to a binary of presence or absence and rasterised the data on a regular spatial grid of 0.5° latitude by 0.5° longitude of the world ocean.

SDMs were applied to predict the habitat suitability for each farmed species on the 0.5° x 0.5° grid of the global ocean. I overlaid the mariculture location data and with the current environmental data; then, the model identified species’ preference profiles for selected environmental conditions identified as important in defining the habitat suitability for mariculture. These environmental conditions, as described in Chapter 3 and 4, included seawater temperature, dissolved oxygen and chlorophyll \(a\) concentration.

Finally, the model incorporated the estimated environmental preferences for each species’ habitat suitability index (HSI) – an index that scales from 0 to 1 to indicate the ecological suitability of the selected environmental conditions in each spatial cell for each studied species with one being the most suitable.

5.2.2.2 **Defining the potential mariculture area**

A potential area for mariculture was defined using two criteria:

1) Based on the work presented in chapter 3, potential mariculture area should be ecologically suitable for the farmed species, i.e., the environmental conditions should be within the species’ tolerance ranges. Suitable areas are defined here as waters with HSI above minimum ecological requirement for optimal growth conditions. Such minimum requirement was described by the minimum threshold or “prevalence,” i.e., the fraction of spatial cells at which the species is present
given specific environmental conditions (Phillips et al., 2009, see chapter 2 for details). I estimated the prevalence (pv) for each species by comparing the estimated HSI of the known farm location with estimates for a predicted new location.

\[ p_{m_i} = 1, \text{ if } HSI_i \geq pv_i \]  
\[ p_{m_i} = 0, \text{ if } HSI_i < pv_i \]

where \( p_{m_i} \) is the potential for mariculture in spatial cell i

2) I assumed that mariculture would not expand beyond the area of national jurisdiction. I also assumed that mariculture could not operate in area where current velocity was below $10 \text{ cm} \cdot \text{s}^{-1}$ or above $100 \text{ cm} \cdot \text{s}^{-1}$ and that mariculture would not operate within marine protected areas (MPAs).

### 5.2.2.3 Projection of future mariculture area and habitat suitability

I projected future marine area suitable for mariculture under climate change using the Earth System Models (ESMs) that are part of the Coupled Models Inter-comparison Project Phase 5 (CMIP5) (see Chapter 4 for details). Specifically, HSI for each species on $0.5^\circ$ latitude by $0.5^\circ$ longitude grid cell of the world ocean was estimated for each year from 1990-2100. Two climate change scenarios were considered: Representative Concentration Pathway (RCP) 2.6 and RCP 8.5, representing the low (‘strong mitigation’) and high (‘business-as-usual’) greenhouse gas emission scenarios, respectively.
5.2.2.4 Projecting future changes in fishmeal and fish oil production

The future availability of FMFO was projected based on the maximum catch potential (MCP) of the major forage fish species their contribution to FMFO uses. For this, I applied a Dynamic Bioclimate Envelope Model (DBEM) (Cheung et al., 2010; Cheung et al., 2016) to project the global MCP of the major forage fish species that were caught for FMFO production (Appendix C) under two climate change scenarios: Representative Concentration Pathways (RCP) 2.6 (“strong mitigation”) and RCP 8.5 (“business-as-usual”) for the period 1950 to 2100. I then calculated the total annual MCP for each species by EEZ and estimated the amount used as FMFO per EEZ based on the corresponding percentage volume used in reduction fisheries for each year as reported in reduction fisheries database. For the simulation period (2015 to 2100), I assumed that the percentage used as FMFO relative to total MCP per EEZ would remain constant as the recent five-year average percentage (2010-2014).

\[
FMFO_{EEZ,t} = \sum_{EEZ,t} MCP \ast PU_{EEZ,t}
\]  

(eq. 2)

where \(FMFO_{EEZ,t}\) is the total fishmeal and fish oil production in per EEZ at year \(t\), MCP is the maximum catch potential per EEZ at time \(t\), PU is the percentage of MCP used as FMFO per EEZ at year \(t\).

5.2.2.5 Modelling potential mariculture production

I quantified an empirical relationship between mariculture potential and related ecological and economic factors across EEZs in the world. Specifically, these factors included the farm-gate price of each species (\(Price\), USD), the total suitable marine area for mariculture of the species per EEZ (\(Area\), km\(^2\)), the average habitat suitability index (\(HSI\)), trophic level and the annual total
fishmeal and fish oil production \((FMFO, \text{ tonnes per year})\) (see equation 3, Table 5.1). I applied a generalised additive model (GAM) using the “gam” function in R package “mgcv” to quantify the relationship between historical mariculture production for each species by EEZ and these drivers of mariculture production. I fitted a gamma family and log link function to the model. Since mariculture of molluscs does not require feed from FMFO, I included different smoothing interaction functions for each species based on whether their farming operations require FMFO. Temporal auto-correlation (1st order) was accounted for as specified by the “CorAR1” term in equation 5. A multi-model comparison framework was used to select the best model with the lowest generalised cross-validation (GCV). The best model has two terms; the parametric and smooth terms. The full GAM model is:

\[
MP_{et} \sim HSI_e + s(Price_e, bs = "cr") + s(FMFO_t, Fac, bs = "fs") + s(TaxonBioTL, bs = "cr") + Area_e + s(Year_t, bs = "cr"), \\
\text{correlation} = \text{corAR1}(0.1113718, form = \sim | \text{Species})
\]  

(eq. 3)

Where MP - the historical mariculture production in tonnes for each EEZ \((e)\) at Year \((t)\)

HSI - the EEZ mean habitat suitability index

Price - the farm-gate price of the species

FMFO – global fishmeal and fish oil production per year

TaxonBioTL – the trophic level of species

Area – total suitable marine area for mariculture

s – smooth function

cr – cubic regression

98
fs - smooth factor interactions with FAC as an identifier

bs - string indicating the (penalised) smoothing basis to use

Using the developed GAM, I predicted the MPP using the “predict.gam” function in the R package “mgcv” (Wood, 2017) with projected changes in HSI, FMFO and suitable marine area for mariculture for 85 farmed species.

Table 5.1. List of model variables and data source.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent</td>
<td>MP</td>
<td>Mariculture production</td>
<td>Tonnes per year</td>
<td>Global mariculture database (Chapter 2)</td>
</tr>
<tr>
<td>Independent</td>
<td>Price</td>
<td>Farm-gate price of the species</td>
<td>USD</td>
<td>Global mariculture database (Chapter 2)</td>
</tr>
<tr>
<td></td>
<td>HSI</td>
<td>the EEZ mean habitat suitability index</td>
<td></td>
<td>Output from the species distribution model</td>
</tr>
<tr>
<td></td>
<td>FMFO</td>
<td>global fishmeal and fish oil production per year</td>
<td>Tonnes per year</td>
<td>Reduction fisheries database (Cashion et al., 2017) and Output from dynamic bioclimatic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>envelope model (Cheung et al., 2016)</td>
</tr>
<tr>
<td></td>
<td>TaxonBioTL</td>
<td>The trophic level of species</td>
<td></td>
<td>FishBase (<a href="http://www.fishbase.org">http://www.fishbase.org</a>); SealifeBase (<a href="http://www.sealifebase.org">www.sealifebase.org</a>)</td>
</tr>
<tr>
<td></td>
<td>Area</td>
<td>total suitable marine area for mariculture</td>
<td>km²</td>
<td>Estimate from species distribution model (Chapter 3 and 4)</td>
</tr>
</tbody>
</table>
5.2.3 Model evaluation

The robustness of the GAM model to predict historical mariculture production was tested. I randomly selected 75% of all historical mariculture production records to develop the GAM and kept the remaining 25% for model testing. I then examined the correlation between predicted values and test dataset using linear regression.

5.3 Results

5.3.1 Estimated decline in fishmeal and fish oil production under climate change

Global FMFO production from forage fish species currently used for FMFO is projected to decrease by 17.7% ± 4.1 (average across ESM and their standard error) by 2050s (average from 2040-2060) relative to 2010s (average from 1995-2015) under RCP8.5. In contrast, under RCP 2.6, global FMFO was projected to decrease by 1.1% ± 0.8 (Table 5.2). Climate change was projected to impact FMFO production from the leading producing countries in lower latitude regions (Figure 5.2). For example, under RCP 8.5, Malaysia, Ecuador and Thailand were projected to have the biggest loss in FMFO production of 82% ± 2.9, 71% ± 5.5 and 67% ± 9.0, respectively (Table 5.3). In contrast, regions such as those around Svalbard Island, Alaska and the Barents Sea are projected to have a gain of 96% ± 5.2, 75% ± 2.8 and 25% ± 6.0 respectively (Figure 5.3).

Table 5.2. Projected percentage change in global maximum catch potential (MCP) of forage fishes in the 2050s (average from 2040-2060) from the current period (average from 1995-2015) under RCP2.6 and RCP8.5. Standard errors of the model averages are provided.

<table>
<thead>
<tr>
<th>Change in global fishmeal and fish oil production (%)</th>
<th>RCP 2.6</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFDL</td>
<td>-2.4</td>
<td>-19.7</td>
</tr>
<tr>
<td>IPSL</td>
<td>-1.0</td>
<td>-14.1</td>
</tr>
<tr>
<td>MPI</td>
<td>-4.8</td>
<td>-19.4</td>
</tr>
<tr>
<td>Model average</td>
<td>-1.14 ± 0.77</td>
<td>-17.7 ± 4.1</td>
</tr>
</tbody>
</table>
Figure 5. 2. Historical and projected catch of forage fishes in the 21st century under RCP2.6 and RCP8.5: a and b) maps of changes in maximum catch potential of forage fishes by the 2050s (average 2040-2060) relative to 2010s (average 1995-2015) under RCP 2.6 and RCP 8.5, respectively; c) 10 year moving average of historical (1990 to 2015) catch (blue line) and model projections (2016 to 2099) under RCP2.6 (red line) and RCP8.5 (blue line).
Table 5. 3. Percentage change in projected fishmeal and fish oil production from the top 15 producing countries in the 2050s relative to the current period under RCP2.6 and RCP8.5.

<table>
<thead>
<tr>
<th>Country</th>
<th>2015 production (x1000 tonnes)</th>
<th>Projected changes in production (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peru</td>
<td>854</td>
<td>2.2 ± 1.5</td>
</tr>
<tr>
<td>Thailand</td>
<td>420</td>
<td>-40.3 ± 5.4</td>
</tr>
<tr>
<td>China</td>
<td>400</td>
<td>-8.2 ± 0.1</td>
</tr>
<tr>
<td>Chile</td>
<td>322</td>
<td>-4.3 ± 1.2</td>
</tr>
<tr>
<td>Vietnam</td>
<td>285</td>
<td>-14.2 ± 3.1</td>
</tr>
<tr>
<td>USA</td>
<td>263</td>
<td>7.7 ± 0.9</td>
</tr>
<tr>
<td>Denmark</td>
<td>206</td>
<td>-32.5 ± 3.5</td>
</tr>
<tr>
<td>Japan</td>
<td>184</td>
<td>13.7 ± 2.7</td>
</tr>
<tr>
<td>Norway</td>
<td>167</td>
<td>-12.2 ± 1.7</td>
</tr>
<tr>
<td>Iceland</td>
<td>153</td>
<td>-60.4 ± 2.8</td>
</tr>
<tr>
<td>Ecuador</td>
<td>125</td>
<td>-32.9 ± 4.4</td>
</tr>
<tr>
<td>Morocco</td>
<td>116</td>
<td>13.4 ± 5.3</td>
</tr>
<tr>
<td>India</td>
<td>103</td>
<td>-3.7 ± 0.14</td>
</tr>
<tr>
<td>Russia</td>
<td>93</td>
<td>16.5 ± 2.1</td>
</tr>
<tr>
<td>Malaysia</td>
<td>90</td>
<td>-56.8 ± 6.2</td>
</tr>
</tbody>
</table>

Note: Country ranking and production figures are from IFFO Fishmeal and Fish oil Statistical Yearbook 2016. Source: www.seafish.org
Figure 5.3. Percentage changes in fishmeal and fish oil production under climate change. EEZs amongst the 15 most projected changes (increase or decrease) in production are shown. The blue dot represents RCP2.6, and the red dot represents RCP8.5. Standard errors of the model averages are provided in the left (blue) and right (red) columns for RCP2.6 and RCP8.5, respectively.
5.3.2 GAM model evaluation
The generalised cross-validation (GCV) score suggested that the model M1 (Table 5.4) is the best model with the lowest GCV score of 4.26. I found a significant positive relationship between the predicted values of mariculture and the historical mariculture production for the randomly selected species ($y = -3.04 + 1.14x$, $p < 0.001$, $R^2 = 0.89$). (Figure 5.4)

Table 5.4. GAM model developed for this study and the corresponding GCV scores.

<table>
<thead>
<tr>
<th>Model</th>
<th>Formula</th>
<th>GCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>$MP \sim HSI + s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Area + Year$</td>
<td>4.26</td>
</tr>
<tr>
<td>M2</td>
<td>$MP \sim HSI + s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Area$</td>
<td>4.27</td>
</tr>
<tr>
<td>M3</td>
<td>$MP \sim HSI + s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Year$</td>
<td>4.35</td>
</tr>
<tr>
<td>M4</td>
<td>$MP \sim s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Year + Area$</td>
<td>4.33</td>
</tr>
<tr>
<td>M5</td>
<td>$MP \sim s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Year$</td>
<td>4.70</td>
</tr>
<tr>
<td>M6</td>
<td>$MP \sim s(Price, k = 100, bs = &quot;cr&quot;) + s(FMFO, Fac, k = 20, bs = &quot;fs&quot;) + s(TaxonBioTL, k = 20, bs = &quot;cr&quot;) + Area$</td>
<td>4.34</td>
</tr>
</tbody>
</table>
Figure 5.4. Predicted mariculture production potential of 25% randomly selected data vs. average historical (1990-2015) mariculture production ($R^2 = 0.89$, $P < 0.001$). The production data were log-transformed. The solid line and the shaded area represent the regression line and 95% level of the confidence interval. The dotted lines represent 1:1 between predicted and reported production.

5.3.3 Future changes in mariculture production potential (MPP) in the 21st century

5.3.3.1 MPP changes relative to 2010s (average from 1995-2015)

Assuming a constant farm-gate price (last five-year average 2011-2015), global MPP from countries that reported a current mariculture production (2011-2015) were projected to increase by $42.4\% \pm 3.2$ (mean and standard error across ESM) and $38.5\% \pm 4.7$ by the mid-21st century (average from 2040-2060) relative to the present-day (average from 1995-2015) under RCP 2.6 and RCP 8.5 respectively (Table 5.5). Similarly, an increase in MPP of $44.0\% \pm 9.8$ under RCP 2.6 and $36.2\% \pm 11.8$ under RCP 8.5 was projected for the end of the 21st century (average from 2080-2100) relative to 2010s.
Table 5.5. Percentage change in global mariculture production potential (MPP) by the mid-(average from 2040-2060) and the end of the 21st century (average from 2080-2100) relative to the 2010s (average from 1995-2015) under RCP 2.6 and 8.5 scenarios. The error represents standard error of projections across different Earth system models.

<table>
<thead>
<tr>
<th>Change in mariculture production potential (%)</th>
<th>Multi-ESM mean and standard error relative to the 2010s (average from 1995-2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The 2050s</td>
<td>The 2090s</td>
</tr>
<tr>
<td>RCP 2.6</td>
<td>42.4 ± 3.2</td>
</tr>
<tr>
<td>RCP 8.5</td>
<td>38.5 ± 4.7</td>
</tr>
</tbody>
</table>

Although global production should increase, the impact of the increase in greenhouse gases will be strong in some countries. Specifically, under both climate scenarios (RCP 2.6 and 8.5), South Africa, Peru, Japan and Canada (Pacific) will loss 70-85% MPP (Figure 5.5). In contrast, Malaysia, Vietnam, Chile, Brazil and China will gain 65-75% under both scenarios.
Species group analysis shows that global finfish MPP will increase under RCP 2.6 and RCP 8.5 (Table 5.6). The model developed in this chapter projected a significant gain in global finfish MPP by 2050s relative to 2010s with 58.8% ± 1.0 and 54.1% ± 5.1% under RCP 2.6 and RCP 8.5, respectively. Under RCP 2.6, finfish MPP will increase in 46 countries and territories while only
35 countries and territories will gain under RCP8.5. The results show a substantial loss in Vietnam (-90.1% ± 1.5), Canada (Pacific) (-90.7% ± 0.7), France (-43.8% ± 1.0) and Chile (-18% ± 4.3) in MPP under RCP8.5 for the same time frame. In contrast, a substantial gain of about 50-70% in finfish MPP was projected in Singapore (71.1% ± 10.3), Portugal (67.2% ± 6.0), China (66.3% ± 4.4) and Norway (46.8% ±15.0) under RCP 8.5 (Figure 5.6).

Table 5. 6. Percentage change in the currently farmed finfish and mollusc species mariculture production potential by mid-century (average from 2040-2060) relative to the 2010s (average from 1995-2015) under RCP 2.6 and 8.5 scenarios. The error represents standard error of projections across different Earth system models.

<table>
<thead>
<tr>
<th>Species Group</th>
<th>RCP 2.6</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finfish</td>
<td>58.8 ± 1.0</td>
<td>54.1 ± 5.1</td>
</tr>
<tr>
<td>Molluscs</td>
<td>38.6 ± 7.6</td>
<td>31.9 ± 7.1</td>
</tr>
</tbody>
</table>
Globally, MPP from molluscs is projected to increase by $39 \pm 7.6\%$ and $32 \pm 7.1\%$ under RCP2.6 and RCP8.5 scenarios respectively by the 2050s relative to the 2010s (Table 5.6). During this period, MPP of molluscs in 45 and 33 EEZs was projected to increase under RCP2.6 and RCP8.5, respectively (Figure 5.7). The EEZs that were projected to have the largest gain in MPP under both
scenarios include Chile, Canada (Pacific) and China. In contrast, South Africa, France and Mexico were projected to decrease in MPP by about 20-85% under RCP 8.5.

Figure 5.7. Percentage change in the currently farmed mariculture production for molluscs potential by the 2050s (average from 2040-2060) relative to the 2010s (average from 1995-2015) under (a) RCP2.6 and (b) RCP8.5 scenarios.
5.3.3.2 MPP changes relative to 2020s (average from 2016-2025)

I tested the sensitivity of the results to the reference period from the 2010s (average from 1995-2015) to 2020s (average from 2016-2025). The sensitivity results show that MPP will decrease substantially in the 2050s relative to 2020s compared to the 2010s. Explicitly, global MPP will decline by 10% ± 2.2 and 16% ± 4.5 under RCP 2.6 and 8.5 scenarios, respectively. Under RCP 2.6, major mariculture producing countries such as China, Chile and Japan will suffer loss 1.1% ± 1.3, 8%± 0.6 and 36% ± 7.1 respectively. While under RCP 8.5, further decline is projected for China (4% ± 1.4), Chile (10 %±1.4), and Japan (41% ±1.9). (Figure 5.8). Similarly, finfish and molluscs MPP are projected to decline in 2050s, relative to 2020s. Under strong mitigation scenarios (RCP 2.6) finfish MPP will decrease by 3% ± 1.0 while molluscs will decrease by 18% ± 2.6. A continuous decline is expected under business-as-usual scenarios (RCP 8.5), Finfish and molluscs MPP will decline by 6% ±5.1 and 30% ± 3.9, respectively.
Figure 5. 8. Percentage changes in mariculture production potential (MPP) for the current 85 most farmed species, limited to countries presently practising mariculture and the selected species farmed, by mid-century (average from 2040-2060) relative to 2020 (average from 2016-2025) under (a) RCP 2.6 (b) RCP 8.5.
5.4 Discussion
5.4.1 Future seafood production from mariculture

Globally, the results of these study suggest that climate change might not have an immediate impact on seafood production from mariculture by the mid-21st century, i.e., in the 2050s relative to 2010s production. This might be due to the initial increase in production from the 1990s throughout 2000s. This result is contrary to the previous studies (Chapter 4) (Froehlich et al., 2018) that claimed climate change might reduce mariculture production through the reduction in suitable marine areas in the 2050s. However, these studies do not consider other primary production inputs in their models but acknowledged that other limiting factors such as FMFO production, farm-gate price and socio-economics play a major role in mariculture expansion and production. The evidence presented in this chapter suggests that marine space is not a limiting factor to mariculture expansion, mariculture only requires about 0.015% of the suitable marine area to supply amount of seafood similar to the catch of marine fisheries (Gentry et al., 2017).

Regionally, some countries’ mariculture industry will be negatively impacted by climate change within this timeframe. The impact will depend on the type of species farmed (i.e. trophic level, aquafeeds requirement). This indicates that the choice of species to the farm is an essential consideration under climate change. Indeed, mariculture has become more heterogeneous and dynamic food sector and mariculture activities, operations and production are unevenly distributed in the world (FAO, 2018). As such, the initial impact of climate change will be local and not global. In 2050s relative to 2010s, ocean warming and acidification would have affected about 34% of the world’s EEZs. Such impacts will affect mainly countries such as Fiji, South Africa, Peru and Malta, where mariculture contributes significantly to nutritional security, livelihood and economy.
(Edwards, 2000; FAO, 2003). Also, aquaculture (and mariculture in particular) is being suggested as a strategic solution to fisheries declines in these regions (Roderburg, 2011), thereby hinders the hope of increasing supply for seafood for food security. Industrialised countries such as Canada, France, USA and Japan face heavy losses with possible impacts on trade, jobs and other social benefits (FAO, 2003; van den Burg et al., 2017).

The effects of ocean warming and acidification will be clearly apparent from the 2020s to the 2050s. The projected changes in Mariculture Production Potential (MPP) by 2050s to 2020s will have a significant implication on global food security. With the expected change of about 10-20 % loss in MPP in Asia, a region which produces more than 80% of total seafood production from mariculture. There is no doubt that, if production potentials translate to actual mariculture production, climate change may have a substantial impact on global seafood production. Also, these will indirectly affect the socio-economic benefits that mariculture brings to Asia (Ahmed and Lorica, 2002). Within this timeframe (2050s relative to 2020s), about 60% mariculture production in EEZs will be impacted with changes in oceanic parameters due to climate change, indicating a further 25% decline in these EEZs in 2010s. These results also highlight that finfish production would be less impacted under climate change compared to molluscs by 2050s relative to both 2010s and 2020s. A similar observation was reported by Froehlich et al. (2018). This might be because of the limited influence of FMFO production decline under changing the climate on Asia finfish production where farming focused mainly on finfish production of the lower trophic level.

In contrast, countries such as Canada, Chile and Spain will lose substantial finfish MPP as these countries focused on farm species with high trophic level. Nevertheless, increased in
molluscs MPP was projected for these countries under climate change. This highlights the need for aquaculture policy that emphasis on farming of lower trophic level that contributes to food net.

5.4.2 Current mariculture development and their sensitivity to climate change impacts

The rapid increase in high trophic level organisms farming is the main concern in terms of the environmental sustainability of mariculture development. Currently, upper topic level species farming such as salmon, shrimps and tuna required the feed that consists of fishmeal and fish oil (FMFO) for dietary nutrients for optimal growth (Deutsch et al., 2007; Tacon and Metian, 2008). Recent mariculture production data (Chapter 2) shows that the percentage of fed mariculture species has surpassed non-fed species. An indication of constant need and usage of protein source particularly FMFO in aquafeed. FMFO is produced from wild captured forage fish (Tacon and Metian, 2008). Aquaculture consumed 3,844,000 tonnes of fishmeal (68.4% of total production) and 782,000 tonnes of fish oil (73.8% of the total output) in 2007 and 2008 respectively (Tacon et al., 2011). Consequently, such demand for wild catches exerts additional pressure on capture fisheries. Ultimately, climate change will reduce the maximum catch potential (MCP) of forage fishes.

Projection from this study provides quantitative impacts of climate change on FMFO production. Notably, MCP in tropical and sub-tropical forage fishes is projected to decrease, resulting in a possible decline in FMFO production. Similarly, ocean warming is projected to lead to an increase in the abundance of forage fish in high latitude regions. However, it is uncertain whether the projected increase in forage fish abundance would increase the supply of fishmeal and fish oil, especially as such reduction fisheries does not currently exist in these regions. In contrast, mid- to low- latitude countries produce the largest proportion of FMFO. Specifically, Peru,
Thailand. China and Chile produced about 60% of total global FMFO production (Cashion et al., 2017). With a projected decline in forage fish production from these countries by the mid-21st century, the global supply of FMFO may also decrease. Nevertheless, the decrease in FMFO supplies may drive adaptation responses by the mariculture industry, such as reducing FMFO use by limiting the use FMFO as a feed ingredient in higher value starter (fry), finisher (grow-out) and broodstock feed only (Tacon and Metian, 2008). Also, efforts have been made for more than a decade to find a replacement for FMFO using plant-based sources (Gómez-Requeni et al., 2004a; Lunger et al., 2006; Patil et al., 2006; Hardy, 2010; Torstensen et al., 2011; Izquierdo et al., 2015).

5.4.3 Model structure

The choice of developing an integrated predictive model by harmonising two algorithms: the species distribution model (SDM) and the generalised additive model (GAM) is to ensure that the predictive model accounts for the climate variations on suitable environmental conditions and the relationship between various mariculture production inputs and MPP.

Specifically, SDMs are tools that link together the species distribution occurrences (i.e., farm locations) with the environmental data (Chapter 3 and 4) (Guisan and Zimmermann, 2000a; Elith and Leathwick, 2009). Generally, SDMs generate a statistical or non-parametric relationship between environmental conditions such as temperature, oxygen, pH, and primary ocean productivity with species’ occurrences, which are then used to define their potential fundamental niche. The models ultimately predict habitat suitability index for the species (Chapter 3), which allows quantifying the best environmental conditions for optimal growth of farmed species and the selection of the suitable marine area for mariculture (Chapter 3).
The GAM is a generalised linear model with a linear predictor involving a sum of smooth functions of covariates (Wood, 2017). GAM permit a broader class of nonlinear relationships between response and predictor variable (Jones and Wrigley, 1995). This property allows the use in fitting the various production inputs in mariculture notably inputs that do not have a linear relationship with production output (i.e. mariculture production in tonnes).

5.4.4 Limitations of the study

In this chapter, I developed new approaches to project future mariculture production potential under climate change; however, various uncertainties are associated with this projection. First, a significant percentage of aquafeed ingredients is from terrestrial-based food production (Gatlin et al., 2007; Troell et al., 2014a; Pahlow et al., 2015). Climate change is projected to alter agriculture production (Fischer et al., 2002; Easterling W. et al., 2007) and potentially, the supply of plant-based aqua-feed ingredients. This may consequently affect MPP in similar ways as the changing supply of FMFO. Second, other environmental hazards such as harmful algal bloom (Gobler et al., 2017), disease prevalence (Leung et al., 2013) and hypoxia zone (Breitburg et al., 2018) could be limiting factors to mariculture production (Froehlich et al., 2018). There is a possibility that these factors will be exacerbated under climate change (Cochrane et al., 2009). However, these factors are not explicitly considered in this study. Third, there are limitations to the use of species distribution model. SDMs may not adequately quantify the species environmental preference (Pearson and Dawson, 2003) because these ranges are determined only by climate variable, equilibrium exists between the realised species range and its potential range by the climate. Mariculture practices such as selective breeding or technological use that could ensure species and the adaptive industry capacity are not considered. Lastly, socioeconomic factors which are not
considered in this present study such as trade, market, consumer’s preference and governance could limit mariculture production.

5.5 Conclusion

This study provides an in-depth understanding of global mariculture production potential and projects the impact of climate change on these productions by deploying quantitative approach. The results highlight that mariculture is a heterogeneous and dynamic food sector and climate change impact will follow this pattern. Overall, global production potential will increase over the next decade but decrease within 2020-2040. Nevertheless, the local impact of increasing greenhouse gases will be apparent in most countries. Although there are uncertainties associated with these results, nevertheless, the finding is useful in informing policymakers with the information required for future food policy development and climate change adaptation management. The model developed in this study will be beneficial for the impact, adaptation and vulnerability research community.
Chapter 6: Scenarios for mariculture development in the twenty-first century using shared socioeconomic pathways

6.1 Introduction

World aquaculture has been growing rapidly over the last few decades, due in part to the increase in demand from the growing human population (UN, 2019) and the increase in per capita income in many societies (FAO, 2018). The contribution from aquaculture to total food fish supply, world economies and employment is also growing (FAO, 2018). Meanwhile, global seafood catches have been declining since the mid-1990s (Pauly and Zeller, 2016). The farming of aquatic organisms in marine and brackish environments - an activity known as mariculture - is seen as a means to increase seafood production to meet the growing demand (FAO, 2018). However, the sustainability of future mariculture is a concern due to its sizeable ecological footprint (Ahmed and Glaser, 2016), the uncertain effectiveness of public policy (Subasinghe et al., 2009) and some negative societal perceptions about mariculture in general (Barrington et al., 2008). Thus, there is a need to identify policy options with scenarios that would allow future mariculture development to be ecologically, economically and socially sustainable. The process of scenarios development will facilitate the identification of future mariculture opportunities and the major concerns for its expansion.

Mariculture development is shaped by social, economic and ecological factors that determine consumer demand and preferences (Bostock et al., 2010). The recent increase in the numbers of farmed marine and brackish species has been attributed to the growing demand for seafood in developed countries (Campbell and Pauly, 2013). Also, consumer preferences towards mariculture products are shaped by changes in demographic characteristics, education, market locality, advertising and marketing (Fernández-Polanco and Luna, 2012). The growing demand for
mariculture products has also spurred technological innovations to improve farm productivity, for example, through enhanced aquafeed formulations and production systems to increase aquafeed and growth efficiency, and decrease prevalence (Serrano, 2005; Mo et al., 2017). Simultaneously, increasing concerns about the environmental impacts of mariculture has promoted the development of technology to improve contaminant control, feed efficiency, disease management, and to minimise farm animal escapes (Bostock et al., 2010).

The changing ocean conditions under climate change represent a potential threat to the future development of mariculture (Silva and Soto, 2009; Williams and Rota, 2010; Pickering et al., 2011a; Callaway et al., 2012; Barange et al., 2018) (see Chapter 3). Projected conditions will result in changes in the physiology of farmed species (growth, reproduction), the ecology of farm areas (suitable environment) and mariculture operations (species selection, site selection and technology) (Handisyde et al., 2006; Lannig et al., 2010; Merino et al., 2010). These biophysical impacts may increase production costs, which would result in increasing food commodity prices (Parry et al., 2004). These, in turn, may affect consumer demand and preference for food fish. However, technological innovation may help reduce climate change impacts and lower the cost of production (Alcorta, 1994).

Developing scenarios of natural, social and technical drivers affecting future mariculture sustainability can help assess the vulnerability of mariculture to global change, and inform the development of adaptation and mitigation policies and actions. To date, the lack of integration between biological, socio-economic and technological factors remains a major gap in vulnerability assessments of the mariculture sector under climate change. Scenarios can help integrate factors from different domains and disciplines, and explore the consequences of uncertainty in answering the “what if” questions (Duinker and Greig, 2007; van Vuuren et al., 2012a). Scenarios analysis
has been widely used in climate research (van Vuuren et al., 2012b) and global environmental impact assessment (GEA) (Duinker and Greig, 2007; van Vuuren et al., 2012a). The rationale for using scenarios is that climate change is a slow process, where decisions today can have irreversible consequences (van Vuuren et al., 2012b). Rather than focusing on a single future outcome, scenarios facilitate the consideration of possible futures (Moss et al., 2010b; van Vuuren et al., 2012a; O’Neill et al., 2014), by developing a range of storylines about how the future might unfold (Biggs et al., 2007).

To facilitate the assessment of climate change impacts, the Intergovernmental Panel on Climate Change (IPCC) developed scenarios for greenhouse gas emissions. The latest set of emission scenarios designed for the fifth assessment report of the IPCC are made up of four Representative Concentration Pathways (RCPs) (Moss et al., 2010b; van Vuuren et al., 2011), each representing different levels of radiative forcing for the earth system in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0 and +8.5 W·m\(^{-2}\) and labelled as RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively) (van Vuuren et al., 2011).

Shared Socioeconomic Pathways (SSPs) were developed to provide complementary explorative scenarios of societal changes to the RCPs and permit comprehensive assessments of climate change impacts, vulnerability and adaptation (O’Neill et al., 2014; van Vuuren et al., 2014). The SSPs are defined as reference pathways describing plausible alternative trends in the evolution of society over a centennial timescale. Five SSPs representing a set of non-sectorial global pathways of societal development were developed (O’Neill et al., 2014) (Figure 6.1).

SSP 1 – The ‘sustainability - Taking the blue road’ scenario assumes that the world moves towards a sustainable path with inclusive development that respects perceived environmental boundaries. Educational and health investments accelerate, contributing to a low global
population. This scenario further assumes a reduction in overall energy and resource use (van Vuuren et al., 2017).

SSP 2 – The ‘middle of the road’ scenario describes a world that does not shift markedly from historical patterns. Development and income growth proceed unevenly, and most economies are politically stable. Technological development continues apace but without fundamental breakthroughs. Fossil fuel dependency decreases slowly. Environmental systems experience degradation. Global population growth is moderate (Fricko et al., 2016).

SSP 3 - The ‘regional rivalry - A rocky road’ scenario describes a world with a primary focus on domestic or at most regional issues — investments in educational and technological development decline. Economic development is slow. There is a low international priority for addressing environmental concerns. Population growth is low in developed countries and high in developing countries (Fujimori et al., 2016).

SSP 4 – The ‘inequality - A road divided’ scenario is a world with highly unequal investments in human capacity that contributes to wide gaps within and across societies. Technology development is high in the high-tech economy and sectors. Dependence on fossil fuels in all income regions decline. Economic growth is moderate in high and middle-income countries and limited in low-income regions. Environmental policies focus on local issues around middle and high-income countries (Calvin et al., 2017).

SSP5 – The ‘fossil-fuelled development - Taking the highway’ scenario describes a world in which the economy grows at a rapid pace with increasing faith in competitive markets, innovation and participatory societies. There is rapid technological progress and development of human capital with substantial investments in health, education, and institutions. The exploitation of fossil
fuel resources increases and societies around the world adopt resource and energy-intensive lifestyles (Kriegler et al., 2017).

Figure 6.1. The Shared Socioeconomic Pathways framework [see (O’Neill et al., 2014; O’Neill et al., 2017)]. Each SSP represents different combinations of challenges to climate change mitigation and adaptation. This study focuses on SSPs in the dotted boxes.

While the above descriptions provide an overarching framework, this study aims to develop a set of mariculture-focused SSPs to assess climate change impacts, risks and vulnerability for the mariculture sector. Specifically, the research focuses on three of the five SSPs; SSP 1 “Sustainability”, SSP 3 “Regional rivalry” and SSP 5 “fossil-fuelled development” (Figure 6.1). I chose to focus on these three narratives because they allow for the elaboration of very distinct and contrasting narratives.
6.2 Methodology

Broadly, the development of storylines for the mariculture SSPs was informed by the past and current trends in mariculture development. These trends were based on published literature and knowledge solicited from experts through a worldwide online survey and a 3-day workshop held in Vancouver (Canada).

Literature review

I reviewed published accounts and employed a qualitative systematic review approach (Finfgeld-Connett and Johnson, 2013) to review key factors that contribute to the expansion and further development of mariculture initiatives. I then divided these factors into six thematic groups: (1) environmental and natural resource use, (2) technology; (3) international trade; (4) policy; (5) economic growth; and (6) demographic trends (Table 6.1).
Table 6.1. Summary of factors selected that contribute to the expansion and further development of mariculture initiatives.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Examples of elements</th>
<th>Key sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental and natural resource use</td>
<td>Suitable environmental conditions for farming; water availability and quality; aquafeed ingredients availability and quality</td>
<td>(Belton &amp; Little, 2008; Bjørndal &amp; Aarland, 1999; FAO, 1984; Hardy, 1990; Hecht, Moehl, Halwart, &amp; Subasinghe, 2006; Hew &amp; Fletcher, 2001; The World Bank, 2006)</td>
</tr>
<tr>
<td>Technology</td>
<td>Technology transfer and development; private investment in technological innovations; public extension service</td>
<td>(FAO, 2012; Hardy, 1990; Hew &amp; Fletcher, 2001; The World Bank, 2006)</td>
</tr>
<tr>
<td>Policy</td>
<td>Poverty reduction programs; food security; rural development; social benefits</td>
<td>(Ahmed &amp; Lorica, 2002; Belton &amp; Little, 2008; Bjørndal &amp; Aarland, 1999; Brummett &amp; Williams, 2000b; FAO, 2012; Hecht et al., 2006; Lanteigne, 2002; Neiland, Soley, Varley, &amp; Whitmarsh, 2001; Rönnbäck, Bryceson, &amp; Kautsky, 2002; Stonich, Bort, &amp; Ovares, 1997)</td>
</tr>
<tr>
<td>Trade</td>
<td>Markets for high value species; globalisation patterns; trade patterns; seafood demand</td>
<td>(Belton &amp; Little, 2008; Bjørndal &amp; Aarland, 1999; Brummett &amp; Williams, 2000b; EFARO, 2016; FAO, 1984, 2012; Neiland et al., 2001; Rönnbäck et al., 2002; Stonich et al., 1997)</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>Foreign earning; Income level distribution; Export market</td>
<td>(Ahmed &amp; Lorica, 2002; Belton &amp; Little, 2008; Bjørndal &amp; Aarland, 1999; Brummett &amp; Williams, 2000b; EFARO, 2016; FAO, 2012; Rönnbäck et al., 2002; Stonich et al., 1997)</td>
</tr>
<tr>
<td>Demographic Trends</td>
<td>Population growth; food security</td>
<td>(Ahmed &amp; Lorica, 2002; Brummett &amp; Williams, 2000b; EFARO, 2016; FAO, 2012; Hecht et al., 2006; Rönnbäck et al., 2002; Stonich et al., 1997)</td>
</tr>
</tbody>
</table>
Survey

I circulated a semi-structured survey to experts to seek expert opinions on factors that contributed to mariculture development. Questions in the survey were drawn from the factors identified from the literature review (see above). The survey included a total of 19 questions with 18 open-ended questions and one close-ended questions (See Appendix E for survey details). Likert scale was used to measure the survey participant’s opinion. Survey participants were selected using three methods;

1) by collating editors’, officers’ and authors’ names and their emails from official statistics documents and published literature about aquaculture;

(2) extracting the names and corresponding emails of all head, personnel and staff of fisheries and aquaculture departments for countries included in the Sea Around Us (www.seaarroundus.org) global mariculture database (Campbell and Pauly, 2013);

(3) using established discussion groups related to aquaculture on social media platform (e.g. Facebook, LinkedIn).

SurveyMonkey, an online survey development cloud-based software was then used to distribute the survey to all participants.

Workshop

An aquaculture expert workshop was held at the University of British Columbia, Canada, from 2nd to 4th December 2018. The workshop brought together nine professionals, including environmental law and policy researchers, aquaculture management researchers, aquaculture economists, industry experts and scenario development researchers. The workshop focused on developing future outlooks for mariculture using SSPs as a scenario development framework. At the start of the workshop, two presentations were given to provide participants with a general
overview of SSPs and expectations in their application to the mariculture sector. Participants were then split into two groups, ensuring a mix of discipline and expertise in each, and asked to discuss factors affecting mariculture development and possible future trends; the relative importance of key drivers of mariculture expansion identified from the survey; and to draft basic storylines for each mariculture SSP (i.e., SSP1, SSP3 and SSP5).

In summary, the workshop followed four key steps:

1) Discuss the main opportunities and concerns about mariculture development based on findings from the literature review, the expert surveys and global mariculture production trends;

2) Group the concerns into wider category (i.e. domains) and identify key drivers;

3) Discuss critical uncertainties;

4) Develop three separate storylines (SSP1, SSP3 and SSP5) taking into account projected trends for each identified key driver based on the SSP framework.

6.2.1 Storyline description for mariculture shared socioeconomic pathways (SSPMs)

At the end of workshop day 1, the study researchers summarised points and key characteristics provided by each group under each SSP and developed narrative (storylines) drafts. On the second day of the workshop, the group discussed the draft storylines and developed a set of second SSP storyline drafts. These drafts were then circulated to all participants for feedback before being finalised by the study researchers into each SSP storylines.
6.2.2 Data analysis

Survey

Descriptive statistics (i.e. means and frequency) were used to summarise and analyse all survey responses. I performed a factor analysis of the mariculture drivers’ data using the psych package (Revelle, 2011) implemented in R (R Core Team, 2018) and identified components with the highest four eigenvalues based on a minimum loading value of 0.5. The survey results were also used to inform the discussion in the subsequent expert workshop.

6.3 Results

6.3.1 Key findings from the survey

Ninety-eight respondents filled and completed the survey. Fifty-five per cent (54) of the respondents worked in high-income countries, 30% (29) in lower-middle-income countries and 15% (15) in upper-middle-income countries while no one work in lower-income countries returned the questionnaire (income classes division is based on World Bank country groups). Respondents that work in aquaculture related disciplines were amongst the largest group of respondents (33%), while those that work in the legal sector were the least represented (1%).

The surveyed experts identified the following issues in no particular order (Figure 6.2) as the main concerns associated with future mariculture development:

1. eutrophication of coastal waters;
2. harmful algal blooms;
3. loss of goods and services from the mangrove system;
4. the marginalisation of small seafood producers;
5. habitat loss and destruction;
6. farmed animal escapes;
7. impact on biodiversity through capture-based aquaculture;
8. fish disease and parasite transfer to wild populations; and
9. effect on forage fishes from capture fisheries.

Based on the results from the survey and factor analysis, five major drivers of mariculture expansion were identified under the four-factor component with the eigenvalues that accounted for 89% of the variance. These drivers include; availability of farm-related technology, continuous population growth, economic growth, availability of local aquafeed ingredients and labour costs (Table 6.2). Human responses to these drivers as identified from the survey included consumer education, effective governance, and development of affordable and efficient technology (see Appendix E for details).

Figure 6. 2. Main social and ecological concerns identified from the survey that contribute to the main issues associated with future mariculture development.
Table 6.2. Factor analysis identifying the main drivers of future mariculture development as identified by the survey. Selected drivers are in red. MR 1-5 represent the factor names as identified using minres method. Factors are arranged in descending order of their variance.

<table>
<thead>
<tr>
<th>Loadings</th>
<th>MR1</th>
<th>MR2</th>
<th>MR3</th>
<th>MR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability of farm-related technology</td>
<td>1.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous population growth</td>
<td>0.775</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access to the international market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong and relevant aquaculture related policy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid economic growth</td>
<td>0.661</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability of local aquafeed ingredients</td>
<td></td>
<td></td>
<td>1.001</td>
<td></td>
</tr>
<tr>
<td>Low aquafeed cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low labour cost</td>
<td></td>
<td></td>
<td></td>
<td>0.502</td>
</tr>
</tbody>
</table>

6.1.1 Review of main opportunities and concerns for mariculture development based on participant discussion

Based on the current status and trends for mariculture production, workshop participants experience, and information gathered from published literature, the exponential growth of the sector, socioeconomic benefits and the impact of unsustainable practices were identified as the main opportunities and concerns for the future of the sector. In 1990, more than 5.6 million tonnes of seafood (excluding aquatic plants) were farmed in marine and brackish water environments. However, by 2015 this figure had increased to about 27 million tonnes. Substantial production operations occur in Asia, with China accounting for 61% of total volume production while other Asian countries contribute about 20% (Chapter 2). Oceania and Africa, on the other hand, only contribute around 0.6% each. Mariculture growth has been ascribed to the growing demand for seafood from developed countries (Campbell and Pauly, 2013) in particular and the increasing global population and their consumption of seafood more generally (Troell et al., 2014b). The mariculture industry earns valuable foreign exchange for production countries and generates jobs across the sector. The farm-gate value for mariculture seafood products was estimated at USD 24
billion in 1990, which increased to about USD 85 billion by 2015 (Chapter2) (FAO, 2018). Also, mariculture expansion and growth are viewed as a way to attract foreign investment, enhance export earnings, and improve countries’ balance of trade (Stonich et al., 1997). Particularly, current mariculture endeavours tended to focus on high value, high trophic levels species such as salmon, tuna and rainbow trout, although there are regional differences. For example, China and Africa mainly farm species with a mean trophic level that is lower than the global mean. The increasing mean trophic level of farmed species in many regions has raised concern about the amount of fishmeal and fish oil (FMFO) used in feeds (Cashion et al., 2017). Other major concerns include the uneven distribution of mariculture production; export-oriented mariculture production with less emphasis on local consumption; and the environmental implications of increasing mariculture production.

6.1.2 Organising opportunities and concerns into domains and identifying drivers

Based on the responses from the expert survey and workshop, I organised the identified drivers associated with opportunities and concerns around mariculture development in the future into four separate domains. The main ideas under these domains are summarised below.

Science and technology

Workshop participants identified technology as the only driver within the science and technology domain. The mariculture sector currently faces many challenges, including combating diseases and parasites; broodstock improvement and closing of the life cycle of farmed species; efficient aquafeed development with reduced impact on capture fisheries; hatchery and grow-out management; and effective methods to reduce environmental impacts (Subasinghe et al., 2003;
Klinger and Naylor, 2012). These issues are likely to continue to represent challenges for the sector for the next decades.

Technological innovations (including biotechnology\(^2\)) have shown a positive impact on the growth, development and diversification of aquatic species farming (Subasinghe et al., 2003). These innovations are the response to increasing societal demand to see the mariculture industry reduce its environmental and ecological impacts (Bostock et al., 2003). Within the sector, technology is perceived as providing solutions to environmental problems such as escape of farm species, eutrophication and nutrient enrichment of the ecosystem, water quality management, reliant on animal protein for aquafeeds, disease, breeding and propagation procedure. For example, recirculating mariculture systems and integrated multi-trophic mariculture (IMTA) systems - that recycle waste nutrients from higher trophic level species into the production of lower trophic level marine species – were both developed to reduce the environmental footprint of mariculture (Troell et al., 2009).

**Society**

Societal consumption behaviour has an influence on world food systems, production, operations, marketing and distribution. These behaviours are complicated to understand as they are nested within interactive societal indicators such as population growth, income and education (Verbeke and Vackier, 2005). Therefore, under the society domain, I focused on the indirect drivers of societal consumption behaviour behaviours that included population, education and consumer preference.

---

The world population is expected to reach 9.7 billion by 2050 (UN, 2019). This population growth is expected to increase global food fish demand. Rapid population growth, increasing wealth and urbanisation will drive the increase in the need for fish products in lower and middle-income countries (Msangi et al., 2013). In high-income countries, a population with higher educational level could have higher fish consumption (Myrland et al., 2000; Shimshack et al., 2007) due to their awareness of the health and nutritional benefit of food fish consumption (Verbeke and Vackier, 2005). Thus, increasing population, and assess to education and information might further increase the demand. On the other hand, consumers play a prominent role in present-day food systems (Eggersdorfer et al., 2016) and the improving knowledge about the nutritional benefit and the environmental footprints of mariculture may increase the demand for more sustainable mariculture products and reduce those that have higher environmental impacts.

**Governance**

An essential component of a sustainable mariculture sector is governance (Salayo et al., 2012; Olsen, 2015). However, the major challenge in mariculture governance is to balance the interaction that connects environmental sustainability, entrepreneurial innovations and social harmony (Hishamunda et al., 2014) without undermining the growth and development of mariculture food system. Mariculture relies on natural resources such as marine and terrestrial environments, nutrient and energy as significant inputs in production. An integral part of governance is to ensure that exploitation of such natural resource within its carrying capacity while protecting investors and maximising societal benefits (Subasinghe et al., 2009). Workshop participants identified two major driving forces that will affect the effectiveness of governance;
1) A holistic mariculture policy is required to establish sustainable mariculture growth and development. The effective policy requires proper, clear and explicitly defined goals for sustainability.

2) Certification has been a useful tool in the aquaculture industry, especially when governance has shifted away from state regulation (Bush et al., 2013). Sustainable seafood certification schemes are viewed as a market-based mechanism and may not have a balanced effect on the different types of mariculture, e.g., small scale versus large scale farming (Swartz et al., 2017). Hence, the effectiveness of certification schemes would partly depend on their impacts on different types of producers in terms of sustainable mariculture growth.

**Economics and trade**

As a significant percentage of mariculture production are exported rather than for domestic consumption (Anderson and Fong, 1997; Belton and Little, 2008; FAO, 2018), participants recognised the efficiency of marketing system as the main driver under economic and trade domain. Food production systems have changed from production- to market-oriented (Meulenberg and Viaene, 1998; Kahan, 2013). Producers have focused on meeting the market needs, particularly with consumer satisfaction on the front line (Pieniak et al., 2013). As seafood market continues to be highly globalised, future mariculture production may follow these trends which centred on the marketing environments worldwide such as economic (i.e. forces of demand and supply) and technological advancement (i.e. biotechnology development) rather than meeting specific local or regional social objectives (i.e. food security). The effectiveness of the market system will impact the fairness of mariculture-related seafood trade, the choice of product (high
or low-trophic level species), and the production cost and consumer affordability of the products (price).

**6.4 SSP storylines for mariculture**

Detailed storylines for each SSP are included below. Domain contribution to the SSPs is summarised in figure 6.3, and key points under each SPP storyline are summarised in Table 6.3.

**SSPM 1-Sustainability: The blue growth mariculture**

Under this scenario the world accounts for the social and economic costs of mariculture environmental degradation through substantial investments in science (including green technology), education and the development of policies guidelines and charters, that are inclusive and promote sustainability as well as environmental auditing, life-cycle assessment, the measurement of environmental performance, and environmental reporting (Welford, 2016). Overall, global mariculture production is high.

**Science and Technology**

- Mariculture technology development and application are high, leading to a gradual reduction in mariculture dependence on marine inputs in operations. This is mainly driven by a breakthrough in aquafeed improvement, which leads to the replacement of the use of wild forage fish fishmeal and fish oil in aquafeed with protein from non-genetically modified sustainable plant and insect-based sources;
- By 2050, reliance on forage fish usage for aquafeed is minimal worldwide, and the availability of wild fish stocks for aquafeed is not (no longer) a barrier to mariculture growth;
- Economic and societal drivers result in a rapid increase in farming of low trophic level species with a focus on increased species diversity and richness. Substantial biotechnology
developments support the farming of these farmed species under closed life cycle conditions (i.e., through well-established breeding procedures and to the exclusion of captured-based mariculture);

- Improved management practices and scientific breakthroughs limit the impacts of disease and parasites on farmed (and wild) fish;
- Advancements in technology are applied to addressing environmental issues related to farm practices.

**Society**

- The world population is low because of investments in good education and health;
- Consumers are aware of environmental and social sustainability issues around seafood;
- Food preferences in most societies rapidly change to diets with low trophic level species, driving the mariculture industry to farm such species;
- Development of mariculture technical knowledge in low and lower-middle-income countries is rapid, because of substantial technology transfer from upper-middle and high-income countries and support of gradual effective international cooperation promoting global mariculture development in all income countries by 2050.

**Governance**

- There is global support for effective governance mechanisms in mariculture and the development of transparent, reliable ecologically sustainable and socially responsible certification schemes;
• Strong corporate responsibility within the industry due to economic incentives and social pressure;

• Certification schemes meet or exceed the minimum substantive criteria related to animal health and welfare, food safety, environmental integrity as well as social considerations (Kittinger et al., 2017);

• Mariculture operations and their development are underpinned by ecosystem-based scientific understanding and adaptive management. Production intensification follows ecological principles (Henriksson et al., 2018; Aubin et al., 2019) with increased investments channelled towards offshore mariculture to increase overall mariculture carrying capacity;

• There are efforts to develop mariculture operations at the community level to meet local food and nutrition security. Such efforts are encouraged and supported by national policy instruments;

• There is high compliance with mariculture regulatory laws due to adequate and appropriate monitoring that is based on strong evidence-based mechanisms, supported by clear ecological standards and indicators on all aspects of sustainable development, including environmental, economic and social;

• Marine spatial planning includes diverse uses of coastal, land and offshore areas (distance from coast > 2 km) that ensures a reduction in mariculture ecological footprint;

• Strong collaboration among ocean users sees a significant decline in intersectoral conflicts.
Economics and trade

- This scenario sees rapid economic growth in low-income and lower-middle-income countries with an increase in per capita income;

- Informed consumer choices lead to an overall decline in seafood price due to high demand for farmed freshwater species and low trophic level mariculture species;

- Globalised trade market through fairness because of average labour costs and production costs;

- Mariculture industry enjoys policies liberalisation, which makes the industry more market and service-oriented and rapid technological development in harvesting, processing, packaging, transportation, marketing and distribution.

SSPM 3-Regional rivalry

Under this scenario, the world shift towards national and regional security issues, especially mariculture products trades. Mariculture technology benefit high-income countries with low patterns in technology transfer. Mariculture production is low under this scenario.

Science and Technology

- The slow growth of mariculture biotechnology brings little change in the diversity of species farmed, the industry dependence fish meal and fish oil from capture fisheries, aquafeed efficiency, reduction in diseases prevalence;

- There are no new breakthroughs in sustainable plant-based or insect-based source replacement for FMFO, causing continuous pressure on fishing for forage fish and the increased reliance on bycatch for aquafeed production;
There are environmental concerns on increase ecological impacts from mariculture especially as the world turns towards regional development of mariculture with the proliferation of unregulated small-scale mariculture systems;

Low, lower-middle and upper-middle-income countries focus on local species because of substantial reliance on traditional methods with lower efficiency in farm production. While high-income countries continue to farm high trophic level species, their operations out low priority on environmental issues;

Diversity of mariculture farmed species is low in low, lower-middle and upper-middle countries. In contrast, high-income countries continue to diversify the farmed species mostly form seedlings and fingerlings that are obtained through capture-based aquaculture production;

High disease prevalence and transfer are caused by high stocking density, poor water quality and environmental degradation. As a result, mariculture contributes to marine biodiversity loss and reduction in recruitment in fisheries.

**Society**

The population is low in high and upper-middle-income countries but high in the lower middle and low-income countries;

Countries support for sustainable mariculture development is weak;

Increasing inequality within and across countries because of racial and nationalistic beliefs, putting self-interests as the priority;
There is an increase in unsustainable farm practices to meet seafood demand because of material-intensive consumption and diet, especially in the upper-middle and high-income countries;

Due to low mariculture production supply from other regions caused by barriers to trade, low and lower-middle-income countries mariculture production becomes low with high production cost and high environmental impact farming systems because of small investments in technology transfers and international cooperation;

The risk of human health increased because of the high contamination of farmed species from pollution and environmental degradation. The health risks are further exacerbated from the increased use of antibiotic and other chemical products to boost farmed species growth.

**Governance**

The weak regional environmental system from management and institutions leads to an increase in conflicts due to reduced space to support mariculture ventures;

Corporative control (few companies own) most of the mariculture sector, especially in high and upper-middle-income countries, leaving out small actors form the industry;

There is a low priority for environmental issues with no effective marine spatial planning.

Regional efforts towards the use of technology to deal with environmental problems or to allow for alternative mariculture development (offshore or otherwise) reduced drastically. Although upper-middle and high-income countries do have some technology and other capacities, there is no global collaboration and technological transfer.
Economics and trade

- Economic growth is slow globally;
- De-globalised trade with limited free and fair trade systems;
- Increase tariffs on mariculture products, especially by high-income countries;
- The market becomes inefficient in ensuring maximum benefits for all market actors. Hence, low and lower middle income countries lose the opportunity to secure revenue from export;
- There is low investment into mariculture because of its high risk;
- In the lower and upper-middle countries, mariculture activities are related to corruption practices specifically in un-sustainable investment;
- The rapid increase in the price of seafood from mariculture due to increase in demand and decline in supply.

SSPM 5-Fossil fuel-driven development: Fast line to mariculture development

SSPM 5 scenario describes the world that is driven by the economic success of industrialised and emerging economies. Mariculture development oriented towards economic growth. Under this pathway, global mariculture is high but not sustainable.

Science and Technology

- The high technological advancement that leads to intensive mariculture development with an emphasis on farming high trophic level species;
- Strong dependence on natural resources and the environment to increase mariculture production;
• The rapid biotechnology helps to improve plant protein source in aquafeed production such technology is largely genetically modified. There are still substantial uses of capture fisheries forage fish for fishmeal and oil production;
• Rapid biotechnology also fosters the application of farmed species breeding practices for some particular species. Capture-based mariculture increased for ocean ranching of high trophic level finfish. Lower species diversity as an intensive monoculture of carnivorous species become economically viable;
• Technology is transferred from high and upper-middle-income countries to low and lower-middle-income countries;
• Low energy prices allow the use of high technological advance farming systems globally;
• Technology is used to solve environmental issues in the context of increasingly intensified aquaculture production, especially disease prevalence.

Society
• The population is high in the upper-middle and high-income countries but low in lower and low-income countries;
• Consumer’s preferences are more materialism with status consumption, which leads the mariculture industry to produce high trophic level species to suit this consumption habit;
• This lifestyle is funded with an economy that is highly dependant on fossil fuel;
• There is a strongly globalised mariculture industry with few actors controlling the sector;
• International cooperation is useful in the pursuit of mariculture related development regarding the volume and value of production with limited environmental sustainability goals.
Governance

- Effective global management and regulations;

- Certification schemes are useful in upper-middle and high-income countries. However, the certification schemes only meet the minimum substantive criteria that are related to animal health and welfare and socio-economic aspects, leaving out environmental integrity as not essential criteria. This is because global trade requires food safety certificates without consideration of the sustainability of management practices in the exporting country;

- Mariculture related institutions are increasingly effective but more oriented towards a competitive market;

- Less competition among sectors as high mariculture production efficiency and increase offshore mariculture reduces space demand especially in coastal waters;

- Inadequate global environmental standards are allowing gradual destruction of ocean habitat and increasing damage on ocean biodiversity;

- There is strong advocacy for spatial planning that avoids ecologically sensitive areas. However, site selection/assessment protocols are conducted with inconsistency in principles and guidelines.

Economics and trade

- There is rapid economic growth in low and lower-middle-income countries which increase mariculture production to foster competitive markets;

- There is a global specialisation in high trophic level species that reduces the diversity of farming;
• Economic policy favours the reliance on free markets to meet increasing demand, especially from mid-income class;

• There is a decline in the prices of seafood from mariculture.

Figure 6. 3. A schematic diagram illustrating the relative contributions of each domain to mariculture sustainability within SSPMs. The scale of each domain is hypothetical and the points were drawn based on the quality description of each SSPM.
<table>
<thead>
<tr>
<th>SSPM element</th>
<th>SSPM 1</th>
<th>SSPM 3</th>
<th>SSPM 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population growth</td>
<td>Global low population</td>
<td>The population is low in high and upper-</td>
<td>The population is high in the upper-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>middle-income countries but high in the</td>
<td>middle and high-income countries but</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lower middle and low-income countries</td>
<td>low in lower and low-income countries</td>
</tr>
<tr>
<td>Economic growth</td>
<td>Rapid economic growth in low-</td>
<td>De-globalised economic</td>
<td>Rapid economic growth, with low and</td>
</tr>
<tr>
<td></td>
<td>income and lower-middle-income</td>
<td></td>
<td>lower-middle-income countries, increasing</td>
</tr>
<tr>
<td></td>
<td>countries with an increase in</td>
<td></td>
<td>exactitude in mariculture production to</td>
</tr>
<tr>
<td></td>
<td>income by a person</td>
<td></td>
<td>foster competitive markets</td>
</tr>
<tr>
<td>Trade</td>
<td>Globalised trade market through</td>
<td>De-globalised trade with limited free and</td>
<td>Global specialisation of high trophic</td>
</tr>
<tr>
<td></td>
<td>fairness</td>
<td>fair trade systems</td>
<td>level species</td>
</tr>
<tr>
<td>Policy</td>
<td>Improved management with</td>
<td>Low perseverance</td>
<td>Global focus solution</td>
</tr>
<tr>
<td></td>
<td>effective regulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Rapid development</td>
<td>Slow development</td>
<td>High technological advancement</td>
</tr>
<tr>
<td>development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aqua-feed production</td>
<td>With a breakthrough in a decrease</td>
<td>No new sustainable plant-based or insect-</td>
<td>Genetically modified replacement</td>
</tr>
<tr>
<td></td>
<td>of capture-fisheries forage</td>
<td>based source replacement breakthroughs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fish as a protein source (i.e.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fishmeal and fish oil) in</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aquafeed with replacement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.3. Continue.

<table>
<thead>
<tr>
<th>SSPM element</th>
<th>SSPM 1</th>
<th>SSPM 3</th>
<th>SSPM 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Farmed species</strong></td>
<td>A rapid increase in farming of low trophic level species but increase species diversity and richness</td>
<td>Low, lower-middle and upper-middle-income countries focus on local species because of substantial reliance on traditional methods with low production output. While high-income countries continue to farm high trophic level species</td>
<td>Capture-based mariculture increased for ocean ranching of high trophic level finfish. Lower species diversity as an intensive monoculture of carnivorous species become economically viable</td>
</tr>
<tr>
<td><strong>Farmed species health and welfare</strong></td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Consumption &amp; diet</strong></td>
<td>Low trophic level farmed species diet Global effective planning</td>
<td>High trophic level farmed species diet No effective marine spatial planning</td>
<td>High carnivorous species diet Strong advocacy for spatial planning that avoids ecologically sensitive areas with inconsistency in principles and guidelines.</td>
</tr>
<tr>
<td><strong>Marine spatial planning</strong></td>
<td>Global effective planning</td>
<td>No effective marine spatial planning</td>
<td></td>
</tr>
</tbody>
</table>

6.5 Discussion

Lessons from a participatory approach

Scenarios play an essential role in the research of global environmental change, and the global SSPs provide the opportunity to consider future socioeconomic conditions. These basic global narratives serve as a guide to the development of regional and sectoral extensions of the scenarios. This chapter extends the basic SSPs to mariculture sector. Available method to develop sector-specific explorative scenarios can be categorised into two types: expert-based approach and
participatory approach. The expert-based approach involves using inputs from multiple experts to identify relevant information for scenario development (Krueger et al., 2012).

The participatory approach encompasses the use of stakeholders in generating the relevant knowledge needed in scenarios modelling. Stakeholders can select appropriate agreeable drivers (direct and indirect) based on their experience. One advantage of the participatory approach is that it involves experts and non-experts (especially local knowledge and end-user in a particular sector) in the formulation and modelling processes (Krueger et al., 2012). As illustrated here, the participatory approach allowed us to integrate diverse knowledge in providing information on possible consequences and their plausibility. Indeed, participatory approach assisted us in avoiding cognitive bias while identifying various future development (Arnott, 2006).

**Interconnectivity in domains within each narrative**

The four domains and drivers identified in this study are essential to the sustainability of mariculture production and operation. There are also strong linkages between each domain within the SSPMs. In Science and technology domain, SSPM 1 technology plays an important role in ensuring environmental sustainability of mariculture through the development of a sustainable solution to aquafeed (Gatlin et al., 2007), diseases (Crab et al., 2012) and the impact of mariculture on biodiversity (Lovatelli and Holthus, 2008). It also indirectly, contributes to the positive public perception that was noted under society domain. In some cases, the technology used in production systems influences public attitudes and consumer behaviour towards food systems (McCluskey et al., 2016). In SSPM 5, technological innovation plays an important role in mariculture production inputs development and efficiency, which create a ripple effect on consumer satisfaction.
Nevertheless, consumer satisfaction and willingness to pay for such innovation rely on consumer education and knowledge with the health risk associated such as technology innovations (Lusk et al., 2014; Vidigal et al., 2015). Also, societal consumption pattern could lead to technological innovations in food systems, e.g. recirculation aquaculture system (see Appendix A) (de la Gándara et al., 2016). However, technological innovation only could not solve environmental challenges related to food system sustainability; instead the need for economic and cultural transformation of a way of life (Smart, 2010; de Bakker and Dagevos, 2011) is indeed a major requirement for sustainable food systems. Under SSPM 3, regional geopolitical fragmentation rather than technology favours the expansion of the types of mariculture that meet the growing demand for material-intensive consumption diet in the upper-middle and high-income countries.

In the societal domain, there is a distinctly different societal view towards sustainable mariculture production among scenarios. In SSPM 1, global cooperation in mariculture technology transfer, investment in education and effective mariculture governance enhance mariculture expansion towards sustainability. Similar global cooperation has been proposed for agriculture sustainability (Toledo and Burlingame, 2006), particularly in the areas of knowledge exchange for crop farmers. On the contrary, society domain in SSPM 5 shows no drive towards sustainable mariculture with limited efforts in achieving environmental sustainability goals. Whereas under SSPM 3, societal cooperation is low with a wide gap between the rich and developing countries. These detachments affect collaboration towards sustainable practices in any food system (Toledo and Burlingame, 2006).

Ineffective governance existed in SSPM 3 and SSPM 5, which contributed to the overall poor realisation of global sustainable mariculture production. In SSPM 3, geopolitical rivalry leads
to decrease cooperation in the creation of effective globally accepted certification schemes with wealthy countries influencing the rule of law (Bush et al., 2013). In contrast, governance in SSPM5 follows strong advocacy for effective governance however, there is inconsistency in principles and guidelines to achieve sustainable path. With upper-middle and high-income countries meeting the minimum substantive criteria for certification schemes that are related to animal health and welfare, food safety, environmental integrity and socio-economic aspects while other countries only maintain food safety procedure (minimum requirement) to promote mariculture trade. In SSPM1, there is global cooperation towards mariculture governance. It should be noted that successful certification schemes should be inclusive to include all stakeholders in the industry, particularly the smallscale farmers (Maertens and Swinnen, 2009).

The efficiency of the marketing system is necessary to ensure maximum benefit to producing countries, minimise production costs and give reasonable prices to consumer (Kumar, 2007). Indeed, marketing system efficiency is important component of food systems economic sustainability (Meulenberg and Viaene, 1998; Coulter and Onumah, 2002). In SSPM 1 and SSPM 5, marketing apparatus ensures efficient harvesting, processing, packaging, transportation, marketing and distribution of mariculture products. However, this progress mainly benefits production countries in mid to upper-income classes and the provision of reasonably priced mariculture products for high-income countries. However, in SSPM 3, lack of free and fair market undermine market efficiency.

6.6 Conclusion

Food systems are dynamic systems that encompass social, economic and biophysical interactions across multiple dimensions (Garnett et al., 2016). Understanding these dimensions required long term scenario analyses. The present study presents the initiation of extending the
basic shared socioeconomic pathway (SSP) (O’Neill et al., 2014; O’Neill et al., 2017) to the mariculture sector. This sectorial extension is intended as a description of plausible future pathways that can serve as a basis for the impact, adaptation and vulnerability (IAV) assessment analyses. Specifically, I adopted the participatory approach in cohering the main issues related to sustainable mariculture production. This study highlights that future sustainability of mariculture will depend on the efficiency of four domains; 1) The science and technology; 2) Society; 3) Governance and 4) Economics and trade. Moving forward is to turn the qualitative narratives described in the study into quantitative elements so that will enable the definition of the future forcing variable necessary for IAV research.
Chapter 7: Synthesis and conclusion

7.1 General conclusion

In the last few decades, there are concerns about the ability of fisheries supply to meet the growing demand for seafood. Most marine fish stocks are at or over their capacity to produce biomass in the long-term because of overfishing (Garcia and Rosenberg, 2010; Mansfield, 2011; FAO, 2016), degradation of habitats and climate change (Cheung et al., 2010; Plagányi, 2019). Mariculture is suggested to be one of the solutions to fill the gap between seafood demand and supply. In Chapter 1, I highlighted that aquaculture in general (including freshwater and marine sectors) currently provides nearly half of food fish production and contributes substantially to the economy of a few producing countries. I also summarised the challenges that aquaculture is facing to provide sustainable seafood for a world with 9-10 billion people by the mid 21st century (Ahmed et al., 2019), especially under climate change.

Changes in ocean conditions as a result of climate change such as warming and acidification will directly impact the physiology and ecology of farmed species in many aquaculture operations (Cochrane et al., 2009). These environmental changes might lead to a reduction in suitable farmed areas and redistribution of farm species from their historical farming region, particularly for species that are farmed using open or semi-open mariculture methods such as salmon farming in net cage. Also, mariculture production potential will decline in most region of the world. Climate change may affect the frequency of outbreaks of disease and harmful algal bloom that indirectly affect mariculture production (Karvonen et al., 2010). Moreover, climate-induced changes in forage fish production may affect the global supply of fishmeal and fish oil for aquafeed. Also, changes in demand for marine farmed species might increase, especially with the decrease in
supply from capture fisheries. Technology might, however, provide solutions to some of these challenges (Hew and Fletcher, 2001; Kagawa et al., 2005). The overarching goal of this dissertation is to address the impact of climate change on seafood from mariculture, by taking into consideration all the critical components of mariculture production including biological, environmental, social and economic factors.

The first step towards assessing the opportunities and challenges that mariculture development is facing is to collate and synthesise existing datasets on mariculture (Campbell and Pauly, 2013). Thus, in Chapter 2, I updated the Sea Around Us global mariculture production database (GMD) with additional data from 2011 to 2015 and created a farm-gate price database with data from 1990 to 2015. Based on these databases, I showed that global mariculture production had increased to 27.6 million tonnes in 2015 from 22.3 million tonnes in 2010. The estimated farm-gate value of mariculture production globally was USD 85 billion in 2015. The two databases are essential for subsequent analysis in the dissertation to project the potential future mariculture production under climate change.

In Chapter 3, I hypothesise that area that is suitable for mariculture is dependent on ocean conditions, particularly for open farming practices. I developed a new database of mariculture locations and quantified the global marine areas with suitable environmental condition for mariculture using species distribution model. I estimated the marine areas within the exclusive economic zones of all countries that are suitable for potential open ocean mariculture activities. I quantified the environmental niche and inferred the global habitat suitability index (HSI) of 102 most commonly farmed marine species using four species distribution models (SDMs). The results show that large potential marine area is suitable for mariculture. Suitable mariculture areas along the Atlantic coast of South America, Caribbean and West Africa appear to be most under-utilised
for farming. However, these areas contributed less than 10% of total mariculture production in the 2000s period (Chapter 2). These results suggest that factors other than environmental considerations such as the lack of socio-economic and technological capacity, as well as aquafeed supply, may have been limiting the potential for mariculture expansion in many areas. The chapter highlights the importance of incorporating socioeconomics factors to understand the opportunities and challenges for future mariculture development.

In Chapter 4, I hypothesised that climate change would impact the location and diversity of mariculture production directly and indirectly (Handisyde et al., 2006). Using the models developed in Chapter 3, I projected climate change impacts on the suitability of the marine area for mariculture and diversity for 85 fish and invertebrate species that are currently being farmed in the world’s oceans. Results of ensemble projections from three Earth system models and three species distribution models show that climate change will reduce the suitable marine area for mariculture, particularly in tropical regions. Also, climate change may lead to a substantial redistribution of mariculture species diversity, with an average of 10 - 40% decline in the number of species being suitable to be farmed in tropical to sub-tropical regions. In contrast, potential mariculture species diversity is projected to increase in the higher latitude under the high greenhouse gas emission (RCP8.5) scenario by the mid-21st century. These results suggest that tropical developing countries and other countries with declining suitable mariculture areas might lose the chance of meeting the United Nation’s Sustainable Development Goals (SDG’s) (FAO, 2017; Singh et al., 2018) mainly if the loss in suitable mariculture area translates to a reduction in growth performance and subsequent reduction in aquaculture production output. These findings also highlight the opportunities and challenges for climate adaptation through a shift in farming species with the loss of mariculture richness. This study provides information that can support
adaptation planning, such as local environmental impacts and potential conflicts with other marine and coastal sectors of mariculture in the future.

While previous studies (Klinger et al., 2017; Froehlich et al., 2018) including chapter 4 of this dissertation focus only on the direct impact of climate change on seafood production from mariculture, Chapter 5 attempts to incorporate other indirect drivers such as fishmeal and fish oil supply, the specific trophic level of farmed species and changes in farm-gate price in projecting changes in potential mariculture production. Specifically, I developed a predictive model that considered the species historical production (in weight), price, suitable marine area for farming, total world fishmeal and fish oil (FMFO) production; and farm species trophic level to project mariculture production potential (MPP). The model explicitly included projected climate change impacts on mariculture production through the modelled changes in suitable marine area for farming and changes in potential catches of species that would contribute to fish meal and fish oil production. The results show that, overall, global production potential will increase over the next decade but decrease within 2020-2040. A strong indication that mariculture can only supplement capture fisheries (Longo et al., 2019), especially under increasing greenhouse gas emissions.

In chapter 6, I hypothesised that socioeconomic scenarios are needed to address the uncertainties of future changes in socioeconomic drivers for mariculture and presented the extended shared socioeconomic pathway narratives for mariculture. Particularly, the future growth and production from mariculture will be largely shaped by socioeconomic drivers (Bostock et al., 2010) such as the availability of aquafeeds, available suitable marine area, efficiency technology, sustainable demand and supply management, the general perception of mariculture practices and the future consumption and diet pattern. Particularly, understanding how these factor changes in the future are important for the assessment of impact, risks and adaptation of the mariculture sector.
under climate change (Moss et al., 2010a; Van Ruijven et al., 2014). The existing shared socioeconomic pathways (SPP) framework (O’Neill et al., 2014; van Vuuren et al., 2014; O’Neill et al., 2017) has been developed to aid climate assessment and evaluate the challenges to mitigation and adaptation to climate change. The SSPs are structured into five narratives. In chapter 6, I presented the mariculture food sector extension to three basic SSP storylines; SSP 1 (Sustainability), SSP 3 (Regional rivalry) and SSP 5 (Fossil fuel-driven development). I employed a literature review, an online survey and an expert workshop to collate information to develop a set of qualitative socio-economic storylines and identified the drivers. Inclusion of expert knowledge through participatory processes helps avoid cognitive bias while developing scenarios for the future (Arnott, 2006). Based on the collated knowledge, I defined four domains: science and technology, society, governance, and economic and trade. These domains are an essential aspect for any future mariculture expansion and development in all regions. Also, the domains and elements described in this chapter will be necessary for mitigation and adaptation strategy consideration under climate change. This sectorial extension of the basic SSP is intended as a description of plausible future pathways that can serve as a basis for the impact, adaptation and vulnerability assessment analyses.

Overall, this dissertation has provided a clear understanding of how climate change will impact seafood production from mariculture. The detrimental effect of climate change will be high in many regions of the world, particularly in the tropics and sub-tropical regions. Coincidentally, some countries in these regions have a high level of nutritional insecurity (Golden et al., 2016). However, mariculture has been promoted to provide seafood to reduce dietary deficiencies in these countries (Liu et al., 2018). Therefore, the long-term sustainability of such mariculture development should consider climate change. Moreover, the future expansion of mariculture in
these regions should also consider the effectiveness of conservation and governance measures (Davies et al., 2019), and the capacity to implement them. In contrast, high latitude regions will gain mostly in mariculture species richness and suitable marine area for farming. Nevertheless, it is uncertain whether these benefits would translate into an increase in mariculture production in these regions, as mariculture production depend strongly on regional socio-economic characterises. The models and databases developed in this dissertation will support continuous mariculture related research and industry applications.

### 7.2 Limitations and uncertainties

The modelling approaches developed in this dissertation supports global assessments of climate change impact on mariculture production, particularly under limited data condition. However, there are some gaps in existing datasets that affect our understanding of climate change threats on seafood production from mariculture. Firstly, as China is responsible for a large proportion of mariculture production in the world, the uncertain credibility of Chinese mariculture data would have large impacts on the trends and projections described in this dissertation (Campbell and Pauly, 2013). Also, mariculture production and farm-gate price data in developing and small Island countries are mostly unsatisfactory and lack credibility because of limited data collection capacities in these regions (FAO, 2018). This dissertation had to rely on these published data. Future research could help improve the mariculture databases but including contributions from local researchers e.g., from China. These researches are likely to have access to a wider range of aquaculture industry reports and other documents where datasets may have been published.

Uncertainties associated with the Species Distribution Model (SDM) have been reviewed by several studies (Elith et al., 2002; Naujokaitis-Lewis et al., 2013; Goberville et al., 2015). There
are limitations regarding the model assumption. For instance, species distribution ranges are determined only by climate variable, the equilibrium that exists between the realised species range and its potential range defined by the climate, the adaptive capacity of the species remain the same in future as of today, and species interactions remain constant in future. These assumptions might make the use of SDM projection inaccurate predominantly in aquaculture practises where farmed species improvement procedure (e.g. genetical modification, hybridisation) (Arai, 2001; Castillo-Juarez et al., 2015; Nguyen, 2016) and technology (Buřič et al., 2016; Bossier and Ekasari, 2017) assist in achieving fast growth and disease resistance species under controlled environment. Also, the projected changes in ocean conditions are based on outputs from earth system models, which are known to have insufficient resolution for coastal processes (Asch et al., 2016). As mariculture often operates in coastal waters, the relatively higher uncertainty of the earth system model projections in such region would also increase the uncertainty of the projected climate impacts on mariculture farmed species.

7.3 Future directions

Climate change is a threat to seafood production from mariculture. There are indirect impacts of climate change on mariculture production that are not considered in this dissertation. One of the challenges to mariculture sustainability is the impact of infectious disease on-farm production (Leung et al., 2013). Disease outbreaks have been considered as a significant constraint to aquaculture development in many countries (Bondad-Reantaso et al., 2005; Defoirdt et al., 2011). Global economic losses from disease outbreaks for aquaculture have been estimated to be about US$6 billion per year since 1990, with the shrimp industry having lost about US$10 billion from 1990 to 2014 (Bank, 2014). Although vaccine (Leong and Fryer, 1993) and antibiotics have been developed and applied to control diseases in aquaculture (Defoirdt et al., 2011), infectious
disease of farmed species could not be eliminated and continues to be significant uncertainty in aquaculture production (McCallum et al., 2003).

The impacts of aquaculture diseases may be exacerbated by extreme weather events and other ocean changes associated with climate change (Karvonen et al., 2010). Ocean warming, sea-level rise and changes in salinity may affect disease occurrence in marine systems (Harvell, 2002). Warming is suggested to affect early life stages (egg and larvae) of pathogens (Stien et al., 2005). Also, socio-economic factors such as stock density of the farm, disease control capacity and degree of globalisation of the farmed species may increase the exposure of farmed organisms to disease, making aquaculture more vulnerable to change impacts (Marcogliese, 2001). Future study should assess how climate change would affect the risk of disease outbreak in mariculture globally by firstly collating available information about the main mariculture related diseases. Secondly, predictive models can be developed to predict mariculture diseases occurrence probability in the future to assess such risks under climate change. The predicted diseases occurrence probability can be used to further refine the predictive model for future mariculture production potential described in chapter 5 of this dissertation.

This dissertation provided a starting point for developing scenarios for mariculture as described by the SSPM quantitative pathways. Next step is to further strengthen the process by providing the qualitative analysis of these narratives. Such scenarios can then be combined with quantitative models to provide more realistic projections of future changes in mariculture production. Also, a regional extension of mariculture SPP will be a useful study to improve our understanding of mariculture production in areas that are particularly vulnerable to climate change impacts as identified in chapter 3 and 4.
Bibliography


IN AQUACULTURE. AGRICULTURE AND ENVIRONMENTAL SERVICES DISCUSSION
PAPER 09. Washington DC; World Bank Group. https://gaalliance.org/wp-


Buschmann, A. H., Cabello, F., Young, K., Carvajal, J., Varela, D. A., & Henríquez, L. (2009). Salmon aquaculture and coastal ecosystem health in Chile: Analysis of regulations,


global ocean under climate change. *Global Change Biology, 16*(1), 24-35. doi:10.1111/j.1365-2486.2009.01995.x


Licence: CC BY-NC-SA 3.0 IGO.


Available online at: https://www.r-project.org/.


https://www.nature.com/articles/ncomms2296#supplementary-information


176


Chicago

UN. (2013). World Economic and Social Survey: Sustainable Development Challenges. . Department of Economic and Social Affairs.


Multiple definitions for aquaculture exist, and this has affected the overall understanding of its principles and practice especially among the general public who liken it to capture fisheries regarding food hunting rather than a food production system (Bacher, 2015). However, aquaculture is distinct because of stock ownership and deliberate intervention in the production cycle (Naylor et al., 2000).

The United States National Aquaculture Act of 1980 defined aquaculture as “The propagation and rearing of aquatic organisms in controlled or selected environments for any commercial, recreational or public purpose” (Banerjee, 1981).

The above definition failed to embrace the understanding of “rearing” in context. In 1988 the Food and Agriculture Organization of the United Nations (FAO) introduced a definition of aquaculture to reduce the confusion between capture fisheries and ocean ranching (Ocean ranching is a type of fish farming in which juvenile fish are released into the ocean to grow unprotected and unassisted to be subsequently harvested (Isaksson, 1988).

This definition is accepted as the modern definition of aquaculture: “The farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants with some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators” (FAO, 2002).
However, this definition lacks the perfection of controlling physiochemical water parameters to make the rearing intervention to be suitable for the aquatic animal to grow and developed in a stress-free environment. Hence, for this dissertation aquaculture will be defined as: “The farming of aquatic organisms including finfishes, crustaceans, molluscs, amphibians and other aquatic animals in a controlled environment (freshwater, marine or brackish) with some intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators”.

**Aquaculture farming systems and practise**

**Extensive aquaculture system**

Extensive aquaculture system is a production system that relies on natural primary productivity of the water body for farmed species nourishment, growth and development. Principally, herbivores and omnivores species are often farmed in an extensive system. These species could be freshwater fish or brackish species such as some Carp (*Cyprinus* spp), Catfish (*Clarias* spp), shrimp (*Penaeus* spp), mullet (*Mugil* spp) and marine species such as bivalve mussels.

- The following features characterise this system of production (Timmons and Ebeling, 2007; Crespi and Coche, 2008);
- Low abiotic and biotic control (e.g. environments, nutrition, predators, competitors, and diseases vectors);
- Low Stocking density with low production yield $< 1000$ kilogram/hectares/year
- High water usage $2100$ l/kg;
• No feeding, dependence on natural food organisms;

• Polyculture- two or more fish species or aquatic organisms cultured together;

High dependence on water quality of natural water bodies (e.g. bays, rivers, dams).

**Intensive aquaculture system**

Intensive aquaculture system involves high intervention in the farming or rearing procedure ranging from feeding, solid waste management, and environmental control. The benefits of the intensive farming system are centred on high return on investment because of high investment and the ability to increase the scale of production by decreasing the cost per unit of output. All aquatic organisms could be farmed with this method.

The following are the characterising feature of the method (Timmons and Ebeling, 2007; Crespi and Coche, 2008);

• High abiotic and biotic control (e.g. environmental parameters- water quality, nutrition, predators, competitors, and diseases vectors);

• High stocking density with high production yield ca. 1,340,000 kg/ha/yr;

• Low water usage 50 litres/kg;

• High quantity feed requirement;

• Monoculture practice only;

• High technology involvement.

**Semi-Intensive aquaculture system**
A distinctive definition for ‘semi-intensive farming system’ has been complicated over the years as the level of supplementary aquafeeds and fertilisation (nutrient enrichment) of the water body is used as an indicator for the system (Nilsson and Wetengere, 1994). The operation may involve the addition of supplemental aquafeeds or other input like aeration and waste management equipment. However, farmed species still partially rely on the primary productivity of the water body for nourishment and optimal water parameters for growth and development.

**Open aquaculture system**

Open aquaculture system is found in freshwater lakes and rivers, coastal waters and offshore. In most cases, net, cage or line/rope is submerged in the aquatic ecosystem to use, which allows free exchange of water from the surrounding environment. The open aquaculture system is considered a high environmental risk method because of its direct contact with the ocean ecosystem. A lot of environmental issues in aquaculture today are related to open systems (Islam, 2005; Olsen and Olsen, 2008). The most commercial open system has been mainly limited to farming of high economic value finfish like bivalves, salmon, cobia, trout, seabass, and seabream (Halwart et al., 2007a). Indeed major mariculture activities are practised with this method.

**Closed aquaculture systems (CAS)**

Closed Aquaculture Systems (CAS) are any system of aquatics organisms production that creates a controlled interface between the farm organisms and the natural environment (CAAR, 2007). Aquatic organisms are typically raised in tanks where they are fed, respired and excreted, with the highly sophisticated waste management procedure which allows water to pass through some compartments for solid waste remover, and biological filtration is thereby making the water
useable several times before discard. A typical example of CAS is Recirculating Aquaculture System (RAS). Example of farmed species currently farmed in RAS includes; *Salmo salar* (Atlantic salmon), *Rachycentron canadum* (Cobia), *Clarias gariepinus* (Catfish), *Oreochromis niloticus* (Tilapia), *Dicentrarchus labrax* (European bass) etc.

**Semi-closed aquaculture systems**

Contrary to open and closed aquaculture systems, a semi-closed aquaculture system is a land-based aquaculture system, in which water is exchanged between the aquaculture holding embankment (Ponds, tanks etc.) and the natural water environment. This system does have a water inlet that allows inflow of fresh (unused) water into the ponds and outflow of wastewater into the natural water environment. Atypical example of this system is Raceways.

**Integrated aquaculture systems**

Integrated aquaculture system is a system of the combined production system of two or more aquatic organisms with or without other agriculture/livestock farming operations in a given space. The rationale for integrated practices is to use the by-products/wastes from one sub-system as a valuable input to another sub-system. An example of such system is Integrated Multi-Trophic Aquaculture systems (IMTA), where lower trophic level species such as seaweed and bivalves are farmed with finfish, thereby improving inorganic and organic nutrient waste recycling, this can reduce the environmental footprint of mariculture farms (Troell et al., 2009) although large commercial IMTA farms are still not common.
Capture-based aquaculture (CBA)

The term capture-based aquaculture first emerged in 2004 (Ottolenghi et al., 2004) since then, the farming of aquatic organism without a controlled breeding process for the production of seed has been termed CBA, and it is defined as;

“The practice of collecting seed material from early life stages to adults from wild and it's subsequent on growing in captivity to marketable size, using aquaculture techniques” (Ottolenghi et al., 2004).

The CBA industry is a diverse worldwide industry because of specific factors such as little technical input, the limited biological and economic feasibility of producing seeds, and wild seeds are usually of high quality (Hermansen and Dreyer, 2008). The development of the industry is solely driven by the market demand for some high-value species whose currently the life cycles cannot be closed on a commercial scale (Ottolenghi et al., 2004). Some example of the species harvested as wild seeds or spats includes; shrimps (*penaeidae*), Tunas (*Thunnus* spp.), Groupers (*Epinephelus* spp).

Closed life-cycle aquaculture or Hatchery- based aquaculture

The production of seeds from hatcheries through manipulation of adult maturation and reproduction and larval or juvenile rearing is called Hatchery- Based aquaculture (HBA)(Sadovy de Mitcheson and Liu, 2008). The process of artificial propagation of seeds largely depends on the aquatic organisms to be farmed. However, inducement of the broodstocks (hypophysation) with or without hormone treatment is the most common method. Afterwards, artificial fertilisation, incubation of eggs and subsequent rearing of larvae would follow. A large number of farmed
species are closed life cycle aquaculture; an example includes; *Salmo salar* (Atlantic salmon), *Rachycentron canadum* (Cobia), *Clarias gariepinus* (Catfish), *Chanos chanos* (Milkfish) etc.

**Production based on the aquatic environment**

Mostly defined by the level of salinity and the species to be farmed, as aquaculture operation or practice can take place in all aquatic ecosystems. Freshwater aquaculture also called Inland aquaculture is the farming of aquatic organisms like molluscs, crustaceans, aquatic plants and fish in water not exceeding 0.5 Practical Salinity Unit (PSU). Freshwater aquaculture contributed 51.4 million tonnes to total aquatic food production in 2016 (FAO, 2018). The subsector makes a substantial contribution to the supply of affordable protein food, particularly in developing countries. Species such as Tilapia spp, Catfishes etc. are farmed in a freshwater environment.

Brackish water farming is the rearing of aquatic organisms where the end product is raised in brackish water, such as estuaries, coves, bays, lagoons, and fjords, in which the salinity generally fluctuates between 0.5 PSU and full-strength seawater (FAO, 2002). Brackish water supports a large number of shrimps and prawn (*Fenneropenaeus indicus* (Indian prawn), *Penaeus monodon* (Giant tiger prawn), *Litopenaeus vannamei* (Whiteleg shrimp) etc.) and finfish (*Anguilla Anguilla* (Short-finned eel), *Oncorhynchus mykiss* (Rainbow trout), *Oreochromis niloticus* (Nile Tilapia). However, most production is recorded aquaculture databases under mariculture or freshwater depends on the level suitable salinity required for the farmed species stress-free growth and development.

Generally, aquaculture in marine and brackish environments is called mariculture. Which is defined as the rearing of the end product takes place in seawater, such as fjords, inshore and
open waters, and inland seas or inland facility (RAS) in which the salinity generally exceeds 20 PSU (FAO, 2002). The subsector produces a large proportion of carnivorous species and bivalves which have high economic value and contributed about 28.7 million tonnes to total global production from farmed aquatic food for human consumption in 2016 (FAO, 2018).
### Appendix B

#### Table B1: List of the primary data source for mariculture database update and farm-gate database

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
</table>
Table B1 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
</table>
Table B1 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
</tbody>
</table>
### Table B2 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
</table>
| **Cyprus**        | 1) DFMR. 2006. Cyprus Marine Aquaculture Production 1988-2005. Data provided by Kyriacou, Y. Department of Fish and Marine Research  
2) Elaborado por: Cámara Nacional de Acuacultura 2009-2015 (Data from Juan Jose Alava, PhD) |
<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>4) IBS. 2004. Yearbook Perikanan Budidaya/Aquaculture. Table: Number of marine culture households, area culture and production by species and province. Indonesian Bureau of Statistics (Badan Pusat Statistik). Jakarta</td>
</tr>
<tr>
<td><strong>Israel</strong></td>
<td>2) BIM 2011-2015. Annual aquaculture survey. Irish sea fisheries board</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
</tbody>
</table>
### Table B1 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>New Caledonia</strong>&lt;br&gt;(France)</td>
<td></td>
</tr>
</tbody>
</table>
## Table B1 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
</tbody>
</table>
3) DAFF (2011-2014) South Africa’s aquaculture yearbook |
<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
</table>


### Table B1 Continued

<table>
<thead>
<tr>
<th>Country/Territory</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country/Territory</td>
<td>Source</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
</tbody>
</table>
### Appendix C

Table B1: List of species in this study.

<table>
<thead>
<tr>
<th>ID</th>
<th>Species</th>
<th>Phylum</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Acanthopagrus schlegeli</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>2</td>
<td><em>Anguilla anguilla</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>3</td>
<td><em>Anguilla bicolor bicolor</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Echinodermata</td>
</tr>
<tr>
<td>4</td>
<td><em>Apostichopus japonicus</em></td>
<td></td>
<td>Marine</td>
</tr>
<tr>
<td>5</td>
<td><em>Argopecten irradians</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>6</td>
<td><em>Argopecten purpuratus</em></td>
<td>Mollusca</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>7</td>
<td><em>Argyrosomus regius</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>8</td>
<td><em>Cerastoderma edule</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>9</td>
<td><em>Chanos chanos</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>10</td>
<td><em>Chlamys farreri</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>11</td>
<td><em>Coregonus lavaretus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>12</td>
<td><em>Crassostrea gigas</em></td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>13</td>
<td><em>Crassostrea rhizophorae</em></td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>14</td>
<td><em>Crassostrea virginica</em></td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>15</td>
<td><em>Decapterus macrdoma</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>16</td>
<td><em>Dentex dentex</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>ID</td>
<td>Species</td>
<td>Phylum</td>
<td>Environment</td>
</tr>
<tr>
<td>----</td>
<td>----------------------------------------</td>
<td>------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>17</td>
<td><em>Dicentrarchus labrax</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>18</td>
<td><em>Diplodus puntazzo</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>19</td>
<td><em>Epinephelus coioides</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>20</td>
<td><em>Epinephelus fuscoguttatus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>21</td>
<td><em>Epinephelus malabaricus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>22</td>
<td><em>Epinephelus polyprhekadion</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>23</td>
<td><em>Epinephelus septemfasciatus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>24</td>
<td><em>Epinephelus tauvina</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>25</td>
<td><em>Gadus morhua</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>26</td>
<td><em>Halioctis discus</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>27</td>
<td><em>Haliotis diversicolor</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>28</td>
<td><em>Haliotis rufescens</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>29</td>
<td><em>Halocynthia roretzi</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td></td>
<td><em>Helicolenus dactylopterus</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td><em>dactylopterus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>31</td>
<td><em>Hippoglossus hippoglossus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>32</td>
<td><em>Lateolabrax japonicus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>33</td>
<td><em>Lates calcarifer</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>34</td>
<td><em>Lutjanus argentimaculatus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>35</td>
<td><em>Lutjanus ehrenbergii</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>ID</td>
<td>Species</td>
<td>Phylum</td>
<td>Environment</td>
</tr>
<tr>
<td>----</td>
<td>--------------------------</td>
<td>-------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>36</td>
<td><em>Lutjanus johnii</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>37</td>
<td><em>Mercenaria mercenaria</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>38</td>
<td><em>Meretrix meretrix</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>39</td>
<td><em>Metapenaeus ensis</em></td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>40</td>
<td><em>Mugil cephalus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>41</td>
<td><em>Acanthopagrus latus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>42</td>
<td><em>Mytilus chilensis</em></td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>43</td>
<td><em>Mytilus coruscus</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>44</td>
<td><em>Mytilus edulis</em></td>
<td>Mollusca</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>45</td>
<td><em>Mytilus galloprovincialis</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>46</td>
<td><em>Oncorhynchus kisutch</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>47</td>
<td><em>Oncorhynchus mykiss</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>48</td>
<td><em>Oncorhynchus tshawytscha</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>49</td>
<td><em>Ostrea edulis</em></td>
<td>Mollusca</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>50</td>
<td><em>Pagellus bogaraveo</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>51</td>
<td><em>Pagrus major</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>52</td>
<td><em>Pagrus pagrus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>53</td>
<td><em>Panulirus ornatus</em></td>
<td>Arthropod</td>
<td>Marine</td>
</tr>
<tr>
<td>54</td>
<td><em>Paralichthys olivaceus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>55</td>
<td><em>Patinpecten yessoensis</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>56</td>
<td><em>Pecten maximus</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>ID</td>
<td>Species</td>
<td>Phylum</td>
<td>Environment</td>
</tr>
<tr>
<td>----</td>
<td>---------------------------</td>
<td>-----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>57</td>
<td>Fenneropenaeus chinensis</td>
<td>Arthropod</td>
<td>Brackish</td>
</tr>
<tr>
<td>58</td>
<td>Penaeus indicus</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>59</td>
<td>Penaeus japonicus</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>60</td>
<td>Penaeus merguiensis</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>61</td>
<td>Penaeus monodon</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>62</td>
<td>Penaeus penicillatus</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>63</td>
<td>Penaeus semisulcatus</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>64</td>
<td>Litopenaeus stylirostris</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>65</td>
<td>Penaeus vannamei</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>66</td>
<td>Perna perna</td>
<td>Mollusca</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>67</td>
<td>Perna canaliculus</td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>68</td>
<td>Perna viridis</td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>69</td>
<td>Pinctada fucata</td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>70</td>
<td>Pinctada maxima</td>
<td>Mollusca</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>71</td>
<td>Plectropomus leopardus</td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>72</td>
<td>Polydactylus sexfilis</td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>73</td>
<td>Polydactylus plebeius</td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>74</td>
<td>Portunus pelagicus</td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>75</td>
<td>Portunus trituberculatus</td>
<td>Arthropod</td>
<td>Marine</td>
</tr>
<tr>
<td>76</td>
<td>Rachycentron canadum</td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>77</td>
<td>Ruditapes decussatus</td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>ID</td>
<td>Species</td>
<td>Phylum</td>
<td>Environment</td>
</tr>
<tr>
<td>----</td>
<td>-----------------------------</td>
<td>----------</td>
<td>----------------</td>
</tr>
<tr>
<td>78</td>
<td><em>Ruditapes philippinarum</em></td>
<td>Mollusca</td>
<td>Brackish</td>
</tr>
<tr>
<td>79</td>
<td><em>Salmo salar</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>80</td>
<td><em>Salmo trutta fario</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>81</td>
<td><em>Salvelinus alpinus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>82</td>
<td><em>Salvelinus fontinalis</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>83</td>
<td><em>Sciaenops ocellatus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>84</td>
<td><em>Scomber japonicus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>85</td>
<td><em>Scophthalmus maximus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>86</td>
<td><em>Scylla serrata</em></td>
<td>Arthropod</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>87</td>
<td><em>Seriola dumerili</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>88</td>
<td><em>Seriola quinqueradiata</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>89</td>
<td><em>Siganus guttatus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>90</td>
<td><em>Sinonovacula constricta</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>91</td>
<td><em>Solea senegalensis</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>92</td>
<td><em>Solea solea</em></td>
<td>Chordata</td>
<td>Marine/Brackish</td>
</tr>
<tr>
<td>93</td>
<td><em>Sparus auratus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>94</td>
<td><em>Takifugu chinensis</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>95</td>
<td><em>Thunnus maccoyii</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>96</td>
<td><em>Thunnus thynnus</em></td>
<td>Chordata</td>
<td>Marine/ Brackish</td>
</tr>
<tr>
<td>97</td>
<td><em>Trachurus japonicus</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
<tr>
<td>ID</td>
<td>Species</td>
<td>Phylum</td>
<td>Environment</td>
</tr>
<tr>
<td>----</td>
<td>---------------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>98</td>
<td><em>Tridacna squamosa</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>99</td>
<td><em>Venerupis pullastra</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>100</td>
<td><em>Metapenaeus dobsoni</em></td>
<td>Arthropod</td>
<td>Marine</td>
</tr>
<tr>
<td>101</td>
<td><em>Saccostrea cucullata</em></td>
<td>Mollusca</td>
<td>Marine</td>
</tr>
<tr>
<td>102</td>
<td><em>Sebastes schlegeli</em></td>
<td>Chordata</td>
<td>Marine</td>
</tr>
</tbody>
</table>
# Appendix D

## Table D1: List of forage fish species used for fishmeal and fish oil

<table>
<thead>
<tr>
<th>ID</th>
<th>Taxon key</th>
<th>Common name</th>
<th>Taxon name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>601888</td>
<td>Alexandria pompano</td>
<td>Alectis alexandrina</td>
</tr>
<tr>
<td>2</td>
<td>604239</td>
<td>American plaice</td>
<td>Hippoglossoides platessoides</td>
</tr>
<tr>
<td>3</td>
<td>600004</td>
<td>Anchoveta</td>
<td>Engraulis ringens</td>
</tr>
<tr>
<td>4</td>
<td>601752</td>
<td>Annular seabream</td>
<td>Diplodus annularis</td>
</tr>
<tr>
<td>5</td>
<td>690016</td>
<td>Antarctic krill</td>
<td>Euphausia superba</td>
</tr>
<tr>
<td>6</td>
<td>601530</td>
<td>Araucanian herring</td>
<td>Clupea bentincki</td>
</tr>
<tr>
<td>7</td>
<td>609256</td>
<td>Arctic skate</td>
<td>Amblyraja hyperborea</td>
</tr>
<tr>
<td>8</td>
<td>601659</td>
<td>Argentine anchovy</td>
<td>Engraulis anchoita</td>
</tr>
<tr>
<td>9</td>
<td>600325</td>
<td>Argentine hake</td>
<td>Merluccius hubbsi</td>
</tr>
<tr>
<td>10</td>
<td>600547</td>
<td>Atlantic anchoveta</td>
<td>Clupea edentulus</td>
</tr>
<tr>
<td>11</td>
<td>600385</td>
<td>Atlantic bumper</td>
<td>Chloroscombrus chrysurus</td>
</tr>
<tr>
<td>12</td>
<td>600069</td>
<td>Atlantic cod</td>
<td>Gadus morhua</td>
</tr>
<tr>
<td>13</td>
<td>601371</td>
<td>Atlantic halibut</td>
<td>Hippoglossus hippoglossus</td>
</tr>
<tr>
<td>14</td>
<td>600024</td>
<td>Atlantic herring</td>
<td>Clupea harengus</td>
</tr>
<tr>
<td>15</td>
<td>600391</td>
<td>Atlantic pomfret</td>
<td>Brama brama</td>
</tr>
<tr>
<td>16</td>
<td>602501</td>
<td>Atlantic wolffish</td>
<td>Anarhichas lupus</td>
</tr>
<tr>
<td>17</td>
<td>600572</td>
<td>Ballan wrasse</td>
<td>Labrus bergylta</td>
</tr>
<tr>
<td>18</td>
<td>601470</td>
<td>Black and Caspian Sea sprat</td>
<td>Clupeonella cultriventris</td>
</tr>
<tr>
<td>19</td>
<td>602508</td>
<td>Black cardinal fish</td>
<td>Epigonus telescopus</td>
</tr>
<tr>
<td>20</td>
<td>600646</td>
<td>Black scabbardfish</td>
<td>Aphanopus carbo</td>
</tr>
<tr>
<td>21</td>
<td>600076</td>
<td>Blackbelly rosefish</td>
<td>Helicolenus dactylopterus</td>
</tr>
<tr>
<td>22</td>
<td>601383</td>
<td>Blue ling</td>
<td>Molva dypterygia</td>
</tr>
<tr>
<td>23</td>
<td>602058</td>
<td>Blue skate</td>
<td>Dipturus batis</td>
</tr>
<tr>
<td>24</td>
<td>600031</td>
<td>Blue whiting</td>
<td>Micromesistius poutassou</td>
</tr>
<tr>
<td>25</td>
<td>600054</td>
<td>Boarfish</td>
<td>Capros aper</td>
</tr>
<tr>
<td>26</td>
<td>601594</td>
<td>Bonga shad</td>
<td>Ethmalosa fimbriata</td>
</tr>
<tr>
<td>27</td>
<td>601587</td>
<td>Brazilian menhaden</td>
<td>Brevoortia aurea</td>
</tr>
<tr>
<td>28</td>
<td>601133</td>
<td>Broad-striped anchovy</td>
<td>Anchoa hepsetus</td>
</tr>
<tr>
<td>29</td>
<td>600093</td>
<td>Bullet tuna</td>
<td>Auxis rochei</td>
</tr>
<tr>
<td>30</td>
<td>600397</td>
<td>Cabinza grunt</td>
<td>Isacia conceptionis</td>
</tr>
<tr>
<td>31</td>
<td>601664</td>
<td>Californian anchovy</td>
<td>Engraulis mordax</td>
</tr>
<tr>
<td>32</td>
<td>600252</td>
<td>Capelin</td>
<td>Mallotus villosus</td>
</tr>
<tr>
<td>33</td>
<td>601608</td>
<td>Chinese gizzard shad</td>
<td>Clupanodon thrissa</td>
</tr>
<tr>
<td>34</td>
<td>600695</td>
<td>Common dab</td>
<td>Limanda limanda</td>
</tr>
<tr>
<td>35</td>
<td>600439</td>
<td>Common dentex</td>
<td>Dentex dentex</td>
</tr>
<tr>
<td>36</td>
<td>604330</td>
<td>Common eagle ray</td>
<td>Myliobatis aquila</td>
</tr>
<tr>
<td>37</td>
<td>602060</td>
<td>Common stingray</td>
<td>Dasyatis pastinaca</td>
</tr>
<tr>
<td>ID</td>
<td>Taxon key</td>
<td>Common name</td>
<td>Taxon name</td>
</tr>
<tr>
<td>----</td>
<td>-----------</td>
<td>---------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>38</td>
<td>601754</td>
<td>Common two-banded seabream</td>
<td>Diplodus vulgaris</td>
</tr>
<tr>
<td>39</td>
<td>600071</td>
<td>Crevalle jack</td>
<td>Caranx hippos</td>
</tr>
<tr>
<td>40</td>
<td>604326</td>
<td>Cuckoo ray</td>
<td>Leucoraja naevus</td>
</tr>
<tr>
<td>41</td>
<td>601706</td>
<td>Damselfish</td>
<td>Chromis chromis</td>
</tr>
<tr>
<td>42</td>
<td>606470</td>
<td>Dusky grouper</td>
<td>Epinephelus marginatus</td>
</tr>
<tr>
<td>43</td>
<td>600066</td>
<td>European anchovy</td>
<td>Engraulis encrasicolorius</td>
</tr>
<tr>
<td>44</td>
<td>600301</td>
<td>European conger</td>
<td>Conger conger</td>
</tr>
<tr>
<td>45</td>
<td>600030</td>
<td>European hake</td>
<td>Merluccius merluccius</td>
</tr>
<tr>
<td>46</td>
<td>600063</td>
<td>European seabass</td>
<td>Dicentrarchus labrax</td>
</tr>
<tr>
<td>47</td>
<td>600785</td>
<td>Flathead grey mullet</td>
<td>Mugil cephalus</td>
</tr>
<tr>
<td>48</td>
<td>600094</td>
<td>Frigate tuna</td>
<td>Auxis thazard</td>
</tr>
<tr>
<td>49</td>
<td>600047</td>
<td>Garfish</td>
<td>Belone belone</td>
</tr>
<tr>
<td>50</td>
<td>601735</td>
<td>Golden grey mullet</td>
<td>Liza aurata</td>
</tr>
<tr>
<td>51</td>
<td>602700</td>
<td>Greater argentine</td>
<td>Argentina silus</td>
</tr>
<tr>
<td>52</td>
<td>600068</td>
<td>Grey gurnard</td>
<td>Eutrigla gurnardus</td>
</tr>
<tr>
<td>53</td>
<td>607045</td>
<td>Grey rockcod</td>
<td>Lepidonotothen squamifrons</td>
</tr>
<tr>
<td>54</td>
<td>607327</td>
<td>Grey triggerfish</td>
<td>Balistes capriscus</td>
</tr>
<tr>
<td>55</td>
<td>601589</td>
<td>Gulf menhaden</td>
<td>Brevoortia patronus</td>
</tr>
<tr>
<td>56</td>
<td>601381</td>
<td>Haddock</td>
<td>Melanogrammus aeglefinus</td>
</tr>
<tr>
<td>57</td>
<td>600374</td>
<td>Indian scad</td>
<td>Decapterus russelli</td>
</tr>
<tr>
<td>58</td>
<td>601663</td>
<td>Japanese anchovy</td>
<td>Engraulis japonicus</td>
</tr>
<tr>
<td>59</td>
<td>601939</td>
<td>Japanese scad</td>
<td>Decapterus maruadsi</td>
</tr>
<tr>
<td>60</td>
<td>600033</td>
<td>Ling</td>
<td>Molva molva</td>
</tr>
<tr>
<td>61</td>
<td>607616</td>
<td>Longnosed skate</td>
<td>Dipturus oxyrinchus</td>
</tr>
<tr>
<td>62</td>
<td>600474</td>
<td>Mackerel icefish</td>
<td>Champsocephalus gunnari</td>
</tr>
<tr>
<td>63</td>
<td>600418</td>
<td>Meagre</td>
<td>Argyrosomus regius</td>
</tr>
<tr>
<td>64</td>
<td>600390</td>
<td>Moonfish</td>
<td>Mene maculata</td>
</tr>
<tr>
<td>65</td>
<td>600334</td>
<td>Orange roughy</td>
<td>Hoplostethus atlanticus</td>
</tr>
<tr>
<td>66</td>
<td>600548</td>
<td>Pacific anchoveta</td>
<td>Cetengraulis mysticus</td>
</tr>
<tr>
<td>67</td>
<td>601520</td>
<td>Pacific herring</td>
<td>Clupea pallasii pallasii</td>
</tr>
<tr>
<td>68</td>
<td>601593</td>
<td>Pacific menhaden</td>
<td>Ethmidium maculatum</td>
</tr>
<tr>
<td>69</td>
<td>600487</td>
<td>Pacific sand lance</td>
<td>Ammodytes personatus</td>
</tr>
<tr>
<td>70</td>
<td>600303</td>
<td>Pacific saury</td>
<td>Cololabis saira</td>
</tr>
<tr>
<td>71</td>
<td>600329</td>
<td>Patagonian grenadier</td>
<td>Macruronus magellanicus</td>
</tr>
<tr>
<td>72</td>
<td>600467</td>
<td>Patagonian toothfish</td>
<td>Dissostichus eleginoides</td>
</tr>
<tr>
<td>73</td>
<td>600482</td>
<td>Pink cusk-eel</td>
<td>Genypterus blacodes</td>
</tr>
<tr>
<td>74</td>
<td>600088</td>
<td>Porbeagle</td>
<td>Lamna nasus</td>
</tr>
<tr>
<td>75</td>
<td>602503</td>
<td>Rabbit fish</td>
<td>Chimaera monstrosa</td>
</tr>
</tbody>
</table>
Table D1 Continued

<table>
<thead>
<tr>
<th>ID</th>
<th>Taxon key</th>
<th>Common name</th>
<th>Taxon name</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>601453</td>
<td>Rainbow sardine</td>
<td><em>Dussumieria acuta</em></td>
</tr>
<tr>
<td>77</td>
<td>600056</td>
<td>Red bandfish</td>
<td><em>Cepola macropththalma</em></td>
</tr>
<tr>
<td>78</td>
<td>600790</td>
<td>Red mullet</td>
<td><em>Mullus barbatus barbatus</em></td>
</tr>
<tr>
<td>79</td>
<td>600331</td>
<td>Roughhead grenadier</td>
<td><em>Macrourus berglax</em></td>
</tr>
<tr>
<td>80</td>
<td>600332</td>
<td>Roundnose grenadier</td>
<td><em>Coryphaenoides rupestris</em></td>
</tr>
<tr>
<td>81</td>
<td>600706</td>
<td>Sand steenbras</td>
<td><em>Lithognathus mormyrus</em></td>
</tr>
<tr>
<td>82</td>
<td>607614</td>
<td>Sandy ray</td>
<td><em>Leucoraja circularis</em></td>
</tr>
<tr>
<td>83</td>
<td>607619</td>
<td>Shagreen ray</td>
<td><em>Leucoraja fullonica</em></td>
</tr>
<tr>
<td>84</td>
<td>600752</td>
<td>Shortfin mako</td>
<td><em>Isurus oxyrinchus</em></td>
</tr>
<tr>
<td>85</td>
<td>600645</td>
<td>Silver scabbardfish</td>
<td><em>Lepidopus caudatus</em></td>
</tr>
<tr>
<td>86</td>
<td>600107</td>
<td>Skipjack tuna</td>
<td><em>Katsuownus pelamis</em></td>
</tr>
<tr>
<td>87</td>
<td>601661</td>
<td>Southern African anchovy</td>
<td><em>Engraulis capensis</em></td>
</tr>
<tr>
<td>88</td>
<td>600320</td>
<td>Southern blue whiting</td>
<td><em>Micromesistius australis</em></td>
</tr>
<tr>
<td>89</td>
<td>600322</td>
<td>Southern hake</td>
<td><em>Merluccius australis</em></td>
</tr>
<tr>
<td>90</td>
<td>604943</td>
<td>Spotted flounder</td>
<td><em>Citharus linguatula</em></td>
</tr>
<tr>
<td>91</td>
<td>600394</td>
<td>Spotted seabass</td>
<td><em>Dicentrarchus punctatus</em></td>
</tr>
<tr>
<td>92</td>
<td>601327</td>
<td>Surmullet</td>
<td><em>Mullus surmuletus</em></td>
</tr>
<tr>
<td>93</td>
<td>600032</td>
<td>Thickback sole</td>
<td><em>Microchirus variegatus</em></td>
</tr>
<tr>
<td>94</td>
<td>602499</td>
<td>Thicklip grey mullet</td>
<td><em>Chelon labrosus</em></td>
</tr>
<tr>
<td>95</td>
<td>604583</td>
<td>Thinlip grey mullet</td>
<td><em>Liza ramada</em></td>
</tr>
<tr>
<td>96</td>
<td>602535</td>
<td>Thresher</td>
<td><em>Alopias vulpinus</em></td>
</tr>
<tr>
<td>97</td>
<td>604642</td>
<td>Tope shark</td>
<td><em>Galeorhinus galeus</em></td>
</tr>
<tr>
<td>98</td>
<td>600384</td>
<td>Torpedo scad</td>
<td><em>Megalaspis cordyla</em></td>
</tr>
<tr>
<td>99</td>
<td>601366</td>
<td>Tub gurnard</td>
<td><em>Chelidonichthys lucerna</em></td>
</tr>
<tr>
<td>100</td>
<td>600051</td>
<td>Tusk</td>
<td><em>Brosme brosme</em></td>
</tr>
<tr>
<td>101</td>
<td>605355</td>
<td>Twaitie shad</td>
<td><em>Alosa fallax</em></td>
</tr>
<tr>
<td>102</td>
<td>601753</td>
<td>White seabream</td>
<td><em>Diplodus sargus sargus</em></td>
</tr>
<tr>
<td>103</td>
<td>600302</td>
<td>Whitespotted conger</td>
<td><em>Conger myriaster</em></td>
</tr>
<tr>
<td>104</td>
<td>600029</td>
<td>Whiting</td>
<td><em>Merlangius merlangus</em></td>
</tr>
<tr>
<td>105</td>
<td>600026</td>
<td>Witch flounder</td>
<td><em>Glyptcephalus cynoglossus</em></td>
</tr>
<tr>
<td>106</td>
<td>600416</td>
<td>Yellow croaker</td>
<td><em>Larimichthys polyactis</em></td>
</tr>
</tbody>
</table>


Appendix E
Marine aquaculture questionnaire

This is part of a study on the future of global aquaculture under global change, led by Oyinlola Muhammed, PhD candidate at the Institute for the Oceans and Fisheries, the University of British Columbia. The primary purpose is to collate expert knowledge about marine aquaculture in the world now and the future. The information you provide will be used to identify ecological, social and economic drivers that could determine the future of global marine aquaculture development.

If you decide to participate, please complete the questionnaire below. Your completion of this questionnaire implies consent to be interviewed. The questionnaire should take about 15 minutes to complete. This project is funded by the Nippon Foundation – Nereus Program (www.nereusprogram.org). If you have any questions about this research, please feel free contact: Muhammed Oyinlola m.oyinlola@oceans.ubc.ca

Thank you very much for your participation!

*1. In what country do you work? (Please note: answers will be attributed to the selected country)

2. Which of the following best describes your current occupation?

Farm management

Farm business and financial operations

Farm design and engineering

Aquaculture related science

Legal

Education, training and extension
Processing and value adding

Trade and sales

Office and administrative support

Academic

Other (please specify)

3. Based on your knowledge, when was commercial marine aquaculture first established in your country?

Before the 1940s

1950s

1960s

1970s

1980s

1990s

2000s

After 2000s

4. Is there any organisation or association that regulates the affairs of the marine aquaculture industry in your country?

Yes
No

Please, give the name of the organisation or association (Optional).

5. Based on your knowledge, which the marine aquaculture industry sector(s) operate in your country?

Breeding/hatchery

Adult grow-out

Aquaculture research

Aquafeed production

Fish processing

Other (please specify)

*6. To the best of your knowledge, what is the proportion of marine aquaculture production that is for export in your country?

Less than or equal 10 %

11 - 20 %

21 - 30 %

31 - 40 %

41 - 50 %

61 - 70 %
71 - 80%

Above 80%

*7. How would you describe the cultural importance of marine aquaculture practice in your
country?

Not important Slightly important Moderately important Important Very important

*8. How vital is marine aquaculture to your country's economy?

Not important Slightly important Moderately important Important Very important

*9. Do you agree that there is much promise in replacing fishmeal as a protein source in aquafeed
with other animals (e.g. insects) and plants (e.g. algae) sources in the future?

highly disagree Disagree Neutral Agree highly agree

*10. The following are possible roles of technology in minimising the environmental and
ecological impacts of marine aquaculture. Based on your knowledge, please evaluate the following roles.

Not important Slightly important Moderately important Important Very important

Limiting the use of natural resources (e.g. forage fish) for aquafeeds.

Limiting the use of natural resources (e.g. forage fish) for aquafeeds.

Reducing nutrient inputs into the ocean.

Reducing the negative impacts on biodiversity caused by wild stocking in marine aquaculture.
Reducing the spread of parasites and diseases from farm stock to the wild.

Minimise/prevent habitat degradation and modification caused by marine aquaculture

11. What practices are being taken/should be taken to reduce the impacts of marine aquaculture on the environment (land/oceans)? Please specify the three most important to you.

1)                                       
2)                                       
3)                                       

*12. How important is government policy in mitigating the environmental and ecological impacts from marine aquaculture? 

Not important Slightly important Moderately important Important Very important

*13. Do you agree with the following policy objectives for marine aquaculture?

Strongly disagree disagree Neutral Agree Strongly agree

Increase local food production thereby combating food security.

Increase country competitiveness in the global marine aquaculture market.

Focus mainly on reducing marine aquaculture activities' impact on the environment.

Focus mainly on the provision of jobs and livelihood

*14. Please indicate your agreement with the following statements.

Strongly disagree Disagree Neutral Agree Strongly agree
The growth and development of your country’s marine aquaculture industry are solely dependent on the economic situation of the country.

Technological development is the major factor to increase future marine aquaculture production. In your opinion, your country has a high potential for marine aquaculture expansion. However, conflict with other marine users is the major barrier to marine aquaculture expansion.

To some extent, cultural and religious beliefs influence marine aquaculture development. Climate change will directly affect marine aquaculture production in the future.

The impact of climate change on forage fisheries is a major threat to the protein source ingredient supply for aquafeeds production.

The main objective of marine aquaculture is to create jobs and livelihoods.

15. What are the five major drivers of marine aquaculture expansion in your country? (Please rank the options)

Availability farm related technology

Continuous population growth

Access to the international market
Strong and relevant aquaculture related policy

Rapid economic growth

Availability of local aquafeed ingredients

Low aquafeed cost

Low labour cost

Strong cultural or religious beliefs related to aquatic animal farming

Access to land and marine space for farming

Access to financial support from the government or non-governmental organisation

16. Which of the options below best describe your involvement in the marine aquaculture industry?

Production

Processing
Research

Aquafeed producer

Policymaker

Academic

Consumer

Other (please specify)

17. How many years of experience do you have in the marine aquaculture industry?

Less than one year

1- 2 years

3- 5 years

6- 9 years

Ten years above

Other (please specify)

18. Have you ever worked with capture fisheries?

Yes

No

19. In which capacity were you functioning?
Which of the following best describes your current occupation?
Based on your knowledge, when was commercial marine aquaculture first established in your country?

Is there any organisation or association that regulates the affairs of the marine aquaculture industry in your country?
Based on your knowledge, which marine aquaculture industry sector(s) operate in your country?

Breeding/hatchery  Adult grow-out  Aquaculture research  Aquafeed production  Fish processing
To the best of your knowledge, what is the proportion of marine aquaculture production that is for export in your country?

How would you describe the cultural importance of marine aquaculture practise in your country?
How important is marine aquaculture to your country’s economy?

- **Important**
- **Moderately important**
- **Not important**
- **Slightly important**
- **Very important**

Do you agree that there is much promise in replacing fishmeal as a protein source in aquafeed with other animals (e.g. insects) and/or plants (e.g. algae) sources in the future?

- **Agree**
- **Disagree**
- **Highly agree**
- **Highly disagree**
- **Neutral**
The following are possible roles of technology in minimizing the environmental and ecological impacts of marine aquaculture. Based on your knowledge, please evaluate the following roles.

**Limiting the use of natural resources (e.g., forage fish) for aquafeeds.**

![Bar chart showing the importance of limiting the use of natural resources for aquafeeds across different income levels and globally.](chart.png)
Reducing nutrient inputs into the ocean.

Reducing the negative impacts on biodiversity caused by wild stocking in marine aquaculture.
Do you agree with the following policy objectives for marine aquaculture?
Increase local food production thereby combating food security.

Focus mainly on reducing marine aquaculture activities' impact on the environment.
Focus mainly on provision of jobs and livelihood.

The growth and development of your country’s marine aquaculture industry are solely dependent on the economic situation of the country.
Technological development is the major factor to increase future marine aquaculture production.

In your opinion, your country has a high potential for marine aquaculture expansion. However, conflict with other marine users is the major barrier to marine aquaculture expansion.
To some extent, cultural and religions beliefs influence marine aquaculture development.

Climate change will directly affect marine aquaculture production in the future.
What are the five major drivers of marine aquaculture expansion in your country? (Please rank the options)

![Graph showing the impact of climate change on forage fisheries and availability of farm-related technology across different income levels and globally.]

The impact of climate change on forage fisheries is a major threat to protein source ingredient supply for aquafeeds production.

Options:
- Agree
- Disagree
- Neutral
- Strongly agree
- Strongly disagree

Availability of farm-related technology across different income levels and globally:
- High income
- Lower middle income
- Upper middle income
- Global
Strong and relevant aquaculture related policy

Rapid economic growth
High income
Lower middle income
Upper middle income
Global

Low aquafeed cost

In what country do you work? (Please note: answers will be attributed to the selected country)

High income
Lower middle income
Upper middle income
Global

Production
Processing
Consumer
Academic
Research
Aquafeed producer
Policy maker
Nippon Foundation-University of British Columbia  
Nereus Program - Workshop on Developing Future Scenario for  
Marine Aquaculture  
Date: Monday, December 3, 2018, to Tuesday, 4 December 2018  
Venue: Hakai UBC IOF Node (Room 216, AERL Building, UBC)

<table>
<thead>
<tr>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sunday, December 2, 2018</strong></td>
</tr>
<tr>
<td>14:00 - 18:00</td>
</tr>
<tr>
<td><strong>Monday, December 3, 2018</strong></td>
</tr>
<tr>
<td>8:00 - 8:45</td>
</tr>
<tr>
<td>8:45 - 9:00</td>
</tr>
<tr>
<td><strong>Session 1.1</strong></td>
</tr>
<tr>
<td>9:00 - 9:20</td>
</tr>
<tr>
<td>9:20 - 9:45</td>
</tr>
<tr>
<td><strong>Session 1.2</strong></td>
</tr>
<tr>
<td>9:45 - 10:05</td>
</tr>
<tr>
<td>10:05 - 10:30</td>
</tr>
<tr>
<td>10:30 - 11:00</td>
</tr>
<tr>
<td>11:00 - 12:30</td>
</tr>
<tr>
<td>12:30 - 13:30</td>
</tr>
<tr>
<td>13:30 - 14:30</td>
</tr>
<tr>
<td>14:30 - 15:00</td>
</tr>
<tr>
<td>15:30</td>
</tr>
<tr>
<td>18:00</td>
</tr>
<tr>
<td><strong>Tuesday, December 4, 2018</strong></td>
</tr>
<tr>
<td>8:00 - 9:00</td>
</tr>
<tr>
<td>9:00 - 9:15</td>
</tr>
<tr>
<td><strong>Session 2.1</strong></td>
</tr>
<tr>
<td>9:15 - 9:45</td>
</tr>
<tr>
<td>9:45 - 10:30</td>
</tr>
<tr>
<td>10:30 - 11:00</td>
</tr>
<tr>
<td>11:00 - 12:00</td>
</tr>
<tr>
<td>12:00 - 13:00</td>
</tr>
<tr>
<td>13:00 - 14:00</td>
</tr>
<tr>
<td>14:00 - 15:00</td>
</tr>
<tr>
<td>16:00 - 17:00</td>
</tr>
<tr>
<td>18:00</td>
</tr>
</tbody>
</table>

244