

SAPEA: Science Advice for Policy by European Academies



FOOD FROM THE OCEANS

SAPEA

Science Advice for Policy by European Academies

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How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?

SAPEA Evidence Review Report No. 1

Informs the Scientific Advice Mechanism High-Level Group of Scientific Advisors
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About SAPEA

Spanning the disciplines of engineering, humanities, medicine, natural sciences and social sciences, SAPEA (Science Advice for Policy by European Academies) brings together outstanding knowledge and expertise from over 100 academies, young academies and learned societies in over 40 countries across Europe.

SAPEA is part of the European Commission Scientific Advice Mechanism (SAM), which provides independent, interdisciplinary and evidence-based scientific advice on policy issues to the European Commission. SAPEA works closely with the SAM High Level Group of Scientific Advisors.

This Evidence Review Report informed the SAM HLG Scientific Opinion on Food from the Oceans, which is available here: <http://ec.europa.eu/research/sam/index.cfm?pg=oceanfood>

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For further information about SAPEA visit: www.sapea.info.

Table of Contents

05	FOREWORD
07	EXECUTIVE SUMMARY
10	1. INTRODUCTION
14	2. FOOD FROM THE OCEANS: STATUS AND DRIVERS FOR INCREASED DEMAND
14	2.1 How much food and biomass are obtained from the ocean today?
16	2.2 FAO and World Bank growth projections for fishery and aquaculture
17	2.3 Main drivers for increased food production
17	2.3.1 Human population growth and expectation of an increased human trophic level
18	2.3.2 Nutrition challenges and nutrition security
19	2.4 The potential for innovation and future game-changers in fishery and mariculture
21	3. THE BIOLOGICAL POTENTIAL FOR AN INCREASED OCEAN HARVEST
21	3.1 How can more food and biomass be obtained by sustainable harvesting of wild populations?
22	3.1.1 By improved sustainable management of existing fisheries
24	3.1.2 By reducing discards and increased utilisation of offals/discards
25	3.1.3 By harvesting wild species that are not, or only marginally exploited, today
28	3.1.4 By harvesting wild stocks of macroalgae
28	3.1.5 By redirecting reduction fisheries to direct human consumption
29	3.2 How can more food and biomass be obtained by sustainable mariculture?
32	3.2.1 General strategy for increasing mariculture
33	3.2.2 Global mariculture production
35	3.2.3 Macroalgae and microalgae culture
39	3.2.4 Biological potential of mariculture of molluscs and other filter feeders
41	3.2.5 Biological potential of fish mariculture
44	3.2.6 Potential sources of LC n-3 rich lipids needed in fish feed
46	3.2.7 Biological potential of crustacean mariculture
47	3.2.8 Integrated multi-trophic mariculture (IMTA)
49	3.3 Uncertainties associated with climate change and pollutants
51	3.3.1 Climate change affects species vital for food production
52	3.3.2 Climate change impacts on ocean harvest and management implications
54	3.3.3 Regional differences in impacts on fisheries and dependencies
55	3.3.4 Climate change impacts on mariculture harvest
58	3.3.5 Aquaculture and wild catch in coastal systems strongly depend on the interaction with the land bordering the coast
59	3.3.6 Impacts of diseases, parasites and pathogens on increasing food production from the ocean
61	3.3.7 Microplastics have an unclear range of impacts on food production from the ocean
61	3.3.8 Increasing seaweed consumption has large uncertainties with regards to food safety
62	3.3.9 Engineering the climate will impact the ocean – the direction of which is unclear

66

4. THE MARKET AND SOCIAL RESPONSE TO NEW CHALLENGES

- 66** 4.1 What are the current and anticipated future cost-efficiencies of various types of production alternatives?
 - 67** 4.1.1 What are efficient production alternatives for wild capture fisheries?
 - 69** 4.1.2 What are efficient production alternatives for mariculture?
 - 70** 4.1.3 Other food and biomass
 - 71** 4.1.4 If production is to be increased, how can one overcome difficulties?
 - 71** 4.1.5 Economic constraints on investments
- 72** 4.2 Societal response to increased production
 - 72** 4.2.1 Public Response/Perception
 - 75** 4.2.2 Corporate social responsibility: what social licences to operate may be envisaged?
 - 76** 4.2.3 SMART Eating
- 77** 4.3 What governance arrangements can help ensure sustainable harvest of increased marine production?
 - 78** 4.3.1 Governance of the seafood sector
 - 80** 4.3.2 What are the implications of new technologies, new species and multi-use of ocean space for governance?
 - 82** 4.3.3. Hard choices involved in increasing ocean food production
 - 83** 4.3.4 What role could subsidies schemes and tailored taxation play?
 - 84** 4.3.5 Is the current multi-level greening policy of the EU for agriculture systems a tool for regional marine resource governance?
- 85** 4.4 Opportunities for the restoration and enhancement of coastal marine ecosystems

89

5. CONCLUSIONS AND OPTIONS FOR HOW MORE FOOD AND BIOMASS CAN BE OBTAINED FROM THE OCEAN

101

6. REFERENCES

129

ANNEX 1. WORKING GROUP MEMBERS

130

ANNEX 2. BACKGROUND TO THE REPORT

132

ANNEX 3. LITERATURE SEARCH STRATEGY STATEMENT

142

ANNEX 4. TABLE 7. IMPACT OF INCREASES IN DIFFERENT FORMS OF FISHING AND AQUACULTURE ON MARINE ECOSYSTEM SERVICES

144

ANNEX 5. GLOSSARY OF KEY DEFINITIONS AND TERMS

149

ANNEX 6. LIST OF ABBREVIATIONS

151

ANNEX 7. LIST OF FIGURES AND TABLES

152

ANNEX 8. ACKNOWLEDGEMENTS

153

ANNEX 9. PUBLIC ENGAGEMENT AND OUTREACH



Foreword

Food from the Oceans is the first Evidence Review Report published by the SAPEA consortium. SAPEA is an integral part of the European Scientific Advice Mechanism (SAM) and this report demonstrates the outstanding commitment and knowledge of experts who were nominated by academies and learned societies.

Interdisciplinarity and world-class expertise from across Europe are SAPEA's core strengths. We assembled two international working groups for *Food from the Oceans*, covering both the natural sciences and the humanities/social sciences.

We were delighted with SAPEA's collaboration with the High-Level Group of Scientific Advisers (HLG), which has proved so effective in *Food from the Oceans*. Our Evidence Review Report informs the Scientific Opinion of the HLG. They are published together, and the aim is for them to be used by the European Commission in planning and policymaking across a range of areas.

Academia Europaea performed the role of Lead Academy for the *Food from the Oceans* Evidence Review Report. It acted as project manager, ensuring that deadlines were met, and outputs were of the highest quality standard. By working well with academies and experts we have met all milestones leading up to and including the final deliverable, the Evidence Review Report itself. We also took a novel approach to public engagement, with encouraging results.

In *Food from the Oceans*, we believe we have established an attractive model for future SAPEA projects. We would like to thank everyone involved in making *Food from the Oceans* a success and express our sincere gratitude to those who have worked hard throughout 2017.



Prof. Günter Stock
Chair, SAPEA Board &
President, ALLEA



Prof. Sierd Cloetingh
President, Academia Europaea &
Member of the SAPEA Board



Executive summary

How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?

- 1** This question on Food from the Oceans was put to the European Scientific Advice Mechanism (SAM) by Commissioner Vella, Commissioner for Environment, Maritime Affairs and Fisheries, on behalf of the European Commission. It was taken up by the SAM High-Level Group of Scientific Advisors, which provides independent scientific advice to the College of European Commissioners to support their decision-making. The SAPEA Consortium, an integral part of the Scientific Advice Mechanism, was asked to produce an **evidence review report** to support the scientific opinion of the High-Level Group.
- 2** This evidence review report examines the question of how the **oceans can help satisfy the global demand for food**, either through the direct production of food or through the harvesting of biomass (wild or cultivated) that can be used as feed in food production. It also addresses how the **socio-economic context** can support more efficient food production, as part of a systems-based approach.
- 3** We have to find new ways to feed a **fast-growing global population**, anticipated to grow from 7.3 billion people in 2015 to 9.8 billion by 2050, according to the United Nations (UN). Not only will there be many more people, but today's **nutritional challenges** (hunger, undernutrition and micronutrient deficiencies), coupled with the **expectations of citizens** in an increasingly prosperous world, where people are eating more meat and fish in their diets, will **intensify the global demand for food and biomass**. Given current trends, total food demand is projected to increase by 60% by 2050, according to the Food and Agriculture Organisation of the UN (FAO), unless demand can be managed more effectively.
- 4** The oceans are home to a **large number of resources that are either not exploited or are marginally exploited currently** and which could improve food security and the wellbeing of humanity. Increased food production from the ocean could release some of the **pressure that has been put on agriculture**, as well as **supporting a range of livelihoods and activities** associated with the fishing and mariculture industries.
- 5** It is clear that **'business as usual' is not sustainable** from social, economic and environmental viewpoints. The environmental footprint and costs associated with today's food production methods and other food system activities are considerable.
- 6** Given today's extensive impact from agriculture and fisheries, it is hard to envision that a significant increase in global food demand will not **diminish some benefits for both present and future generations**. Therefore, the question posed might be redefined as follows:

How can more food and biomass be obtained from the oceans in a way that maximises the benefits for future generations?

- 7** Earlier in 2017, work began on *Food from the Oceans*, based on a scoping paper from the Commission (SAM, 2016). SAPEA set up two **international and interdisciplinary working groups**, selected primarily on the key criterion of scientific excellence but also with a view to ensuring fair representation in terms of gender, geographical spread etc. The working groups met five times in all, during May and June.
- 8** A **literature review** was conducted, based on the rapid review method, which takes a rigorous but streamlined approach to synthesising evidence.
- 9** In line with its commitment to **public engagement and outreach**, SAPEA also organised a programme of activities aimed at the general public in Europe.
- 10** This evidence review report puts forward a number of **options** for how more food and biomass could be obtained from the ocean. These options group into four main categories: (1) improvements in management and increased utilisation of wastes in the traditional capture fisheries, (2) fishing on new wild species that are not, or only marginally, exploited today, (3) mariculture of organisms that extract their nutrients directly from the water, and (4) mariculture of organisms that require feed.
- 11** In essence, there is only one way to obtain significantly more food and biomass (> 100 Mt) from the ocean: to harvest seafood that, on average, is from a lower trophic level than today. Mariculture appears closest to such a realisation.
- 12** The different options identified were:
 - **Improve management of the established fisheries on wild species**, which can potentially increase the global annual catch of seafood.
 - Tackle the problem of discards and other wastes
 - › **Reduce discards**, by developing selected harvesting, or by landing and using them.
 - › **Utilise discards and other post-harvest wastes**, by processing them.
 - **Redirect part of the landings from reduction fisheries into human consumption.**
 - **Harvest wild animal species at lower trophic levels**, which today are either not exploited at all, or only marginally.
 - **Support the mariculture of**
 - › **Macroalgae.**
 - › **Marine herbivores**, such as bivalves and other filter feeders.
 - › **Marine carnivores.**
 - **Integrate multi-trophic aquaculture (IMTA).**
 - **Support rights-based management**, as a means to smoothing out the supply of wild fish over time.

- **Support start-ups**, by clear, transparent and harmonised rules and regulations, in support of mariculture initiatives.
 - **Ensure the long-term viability of start-ups** by awarding social licences to operate.
 - **Provide trustworthy consumer information**, to promote initiatives on discards and mariculture.
 - **Cultivate new approaches to social responsibility**, which focus on open innovation, co-production of knowledge and social responsibility on multiple levels.
 - **Involve citizens and other relevant stakeholders** in planning processes and in awarding social licences to operate.
 - **Prioritise resulting new jobs** in areas within reach of existing fishing communities.
 - **Introduce financial strategies** that promote sustainable fishing.
 - **Design new coastal and offshore engineering developments**, to enhance both the ecosystem and the production of specific food species.
- 13** This evidence review report was scrutinised at a **scientific expert workshop** held in September 2017, focusing on the feasibility of the options put forward. It was also **peer-reviewed** by experts in October, with further revisions made in response to the feedback.
- 14** The policy recommendations of the High-Level Group and the evidence-based options set out in this evidence review report were examined at a **stakeholder workshop** of representatives from industry, policy and civil society in November.
- 15** Both documents were handed over to the European Commission at the end of November. They are designed to work in tandem. The intention is that they will be used in the planning of the EU's future political priorities and resource allocation. These include the preparation of the Commission's post-2020 Multi-Annual Financial Framework (MFF), the successor to the European Maritime and Fisheries Fund, and a range of other policy areas such as the implementation of the *Blue Growth Strategy*, Agenda 2030, ocean governance and development cooperation.

1. Introduction

There is a need to find new ways to feed a fast-growing global population. Such growth, combined with today's nutritional challenges (hunger, undernutrition and micronutrient deficiencies) and the expectations of citizens in an increasingly prosperous world, will intensify the global demand for food and biomass. This report examines the question of how the ocean can help satisfy the global demand for food (SAM, 2016), either through the direct production of food or through harvesting biomass (wild or cultivated) that can be used as feed in food production. The exercise introduces

Given the current trends, total food demand is projected to increase by 60% by 2050 unless demand can be managed more effectively.

a fundamental dilemma, which is, are we looking at the ocean as a natural heritage to be preserved and protected, or as a 'farm', with produce to be harvested; and to what degree may the two interests be reconciled?

Increased supplies of food from both marine and terrestrial sources, together with modern medicine, have enabled the exceptional growth of the human population over the last century. There is, however, an increased realisation of the extensive environmental footprint and costs associated with today's food production methods (Godfray et al., 2010; Crist, Mora, & Engelman, 2017) and other food system activities (Westhoek, Ingram, van Berkum, Özay, & Hajer, 2016). Land conversion for crop and animal agriculture is considered to be the chief driver of terrestrial habitat loss and biodiversity reduction, as well as other aspects of environmental degradation. This, together with the other food system activities of processing, transporting and retailing, is seen as a substantial contributor to climate change (ter Meulen et al., EASAC, 2017, in preparation). Food production and other food system activities are therefore already making a substantial contribution to crossing planetary boundaries (Steffen et al., 2015; Rockström et al., 2009; Campbell et al., 2017). Crist et al. (2017) also note that the current levels of food production exceed that required to conserve the Earth's biodiversity. It can be argued that, in order to sustain biodiversity and

human wellbeing, actions to slow and eventually reverse population growth are required. However, according to the UN projections of population growth (United Nations, 2015a), this is not going to happen within the foreseeable future and, given the current trends, total food demand is projected to increase by 60% by 2050 (FAO, 2012b), unless demand can be managed more effectively.

While managing demand for food will therefore be increasingly important (Ingram, 2017), there is no doubt that there will be an increased demand for both food and biofuel, particularly from the rising level of wealth in lower and medium income countries in which seafood represents an important driver for dietary and cultural changes (Kharas, 2010). This will put further pressure on the conversion of land to crops and on freshwater resources, in a world where agriculture already accounts for 40% of the earth's land surface usage and 70% of the world's use of fresh water (ter Meulen et al., EASAC, 2017, in preparation). Agriculture is also strongly dependent on the industrial production of fertilisers. Space, water and inorganic nutrients (i.e. fertilisers) are abundant in the ocean and, with this perspective, the ceiling for increased food production appears more severe on land than in the ocean (Duarte et al., 2009). Consequently, attention to increased utilisation of the ocean as a human food provider seems inevitable (EASAC, 2016). Increased food production from the ocean may release some of the pressure that has been put on agriculture to achieve UN sustainable development goal SDG2 (*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*) and SDG12 (*Protect, restore and promote sustainable use of terrestrial ecosystems*).

However, this needs to be achieved without compromising SDG14 (*Conserve and sustainably use the oceans, seas and marine resources*), whilst acknowledging the climate change drivers that are addressed in SDG 13 (climate action).

'Business as usual' is not sustainable from social, economic or environmental viewpoints, and will not lead to higher fishery landings. The World Bank (2013) and FAO (2016b) project more or less invariant capture fishery for the next 10-15 years. In addition, climate change might have a negative impact on oceanic as well as terrestrial food production systems. For example, one recent climate projection forecasts global maximum catch potential to decrease by around 8% by 2050, with decreases in the tropics and increases in high latitudes (Lam, Cheung, Reygondeau, & Sumaila, 2016).

Increased harvest does not necessarily deprive future generations of *overall* benefits, but is likely to change the composition of future *ocean* benefits. The need for more food production, whether it takes place on land or in the ocean, implies a trade-off situation. Given today's extensive footprint from agriculture and fisheries, it is hard to envision that a significant increase in the global food demand will not diminish some benefits for future, as well as present generations. Thus, a rephrasing of the condition of the original question '*How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits*' seems required, i.e. '*in a way that minimises the reduction of the benefits for future generations*' or, in simpler wording, '*in a way that maximises the benefits for future generations*'. Ultimately, the choices underlying such maximisation,

and whether the ocean and land will be viewed in isolation or in combination, are political rather than scientific. However, science can help to map the positive and negative consequences of such a choice, which the present report attempts to do.

While agriculture provides for around 98% of the human need for energy (calories), seafood contributes to essential nutrients (proteins and micronutrients, including essential fatty acids), for billions of people. Seafood and seafood products are the most traded global food commodities, and the proportion of harvested (and cultured) fish being internationally traded has steadily risen, from 8 Mt (Million metric tonnes) (25%) in 1976 to 58 Mt (37%) in 2012 (FAO, 2014). Around 1.25 billion (10⁹) people worldwide rely on fish as their primary source of animal protein, and 4.3 billion people derive at least 15% of their animal protein intake from it (FAO, 2012a). However, global capture fisheries have been stable in the last two decades, and mariculture (i.e. not including freshwater-based aquaculture) production, while growing swiftly in some parts of the world, is still smaller than capture fisheries. At the same time, affluent Western customers are increasing their intake of seafood, as part of taking up a healthier lifestyle. If the current consumption trajectories are maintained, seafood prices will rise, and poorer parts of the global, and also European societies, may find seafood increasingly inaccessible. It is a trend only avoidable if global production is increased (Krause et al., 2015). A wide range of activities associated with the fishing and mariculture industries (which include coastal aquaculture) provides for livelihoods all along the food chain, thereby contributing to poverty reduction, prosperity, and other social and political capitals.

The availability of food supply, together with the previously-mentioned socio-economic factors, are essential to food security, as is obvious by the following FAO (2012a) definition:

...a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences, for an active and healthy life.

As the definition indicates, the key issue for food security is access to food, but food availability and utilisation are also important. Each of these three 'components' comprises a number of 'elements' (Figure 1), all of which need to be stable (other than increasing, if too low) for food security to be met.

Despite the clear contribution marine-sourced food makes to food security, FAO (2017a) suggests that the policy agenda of the fisheries and aquaculture sectors generally undervalues their importance to food security and nutrition, as well as providing direct and indirect income options and contributing to livelihoods. In-depth analysis is still needed around issues of access and affordability, which are often disregarded in policy papers.

This report addresses the question of how more food and biomass can be obtained from the oceans in four sections, as follows:

In **Section 2** of the report, we summarise today's situation concerning the food obtained from the ocean, and briefly review some of the main drivers for the increased demand for food. The issues are further compounded by deficiencies

Food security, i.e. **stability** over time for:

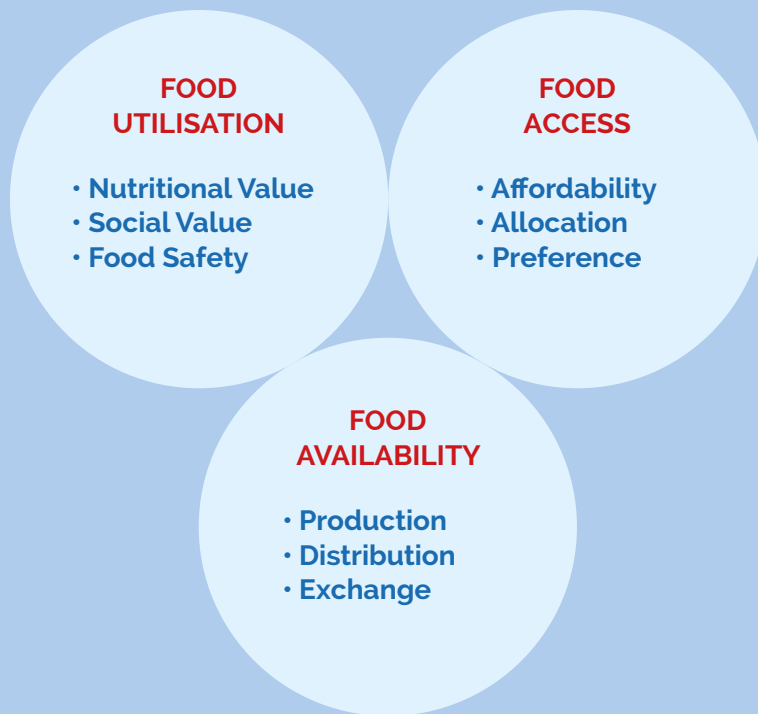


Figure 1. (Ingram J., 2011). The three major components of food security (availability, access and utilisation), and their respective elements.

of knowledge; we may have case-study evidence for some issues, but often generalised knowledge is lacking. The report considers such fields of uncertain knowledge, based on the best-available evidence and considered opinion.

Section 3 looks into:

- The biological potential for increasing the ocean's harvest;
- Today's biological and technological constraints for a realisation of this potential; and
- Uncertainties related to future climate change and pollution that might affect the biological potential.

How to increase the capacity of food production, however, cannot be answered from a biological perspective only and needs to be addressed in a more comprehensive way (Figure 1).

In **Section 4**, we consider bio-economical concerns, ethical choices and social impacts. Any sustainable way forward must consider societal support for how we can best use the resources available to us.

Section 5 summarises the findings of the two previous parts and presents options for how more food and biomass can be obtained from the ocean.



2. Food from the oceans: status and drivers for increased demand

2.1 HOW MUCH FOOD AND BIOMASS ARE OBTAINED FROM THE OCEAN TODAY?

A widely-used figure published by FAO (2016b, Figure 1) shows a linear increase in fish production, from ~20 Mt in 1950 to over 160 Mt in 2014, with capture fisheries stagnating at ~80 Mt since the 1990s and aquaculture producing more fish than capture fisheries for the first time in 2014. These numbers include freshwater aquaculture and freshwater capture fisheries, which are not targeted in the present report. In this report, food and biomass from the ocean are defined as follows:

Marine organisms that have spent most of their life in the ocean and that derive an essential part of their nutrition from the ocean.

The ocean here refers to the marine environment and coastal areas are included in the definition. Throughout the report, we use the word 'mariculture' when referring to aquaculture taking place in the marine environment.

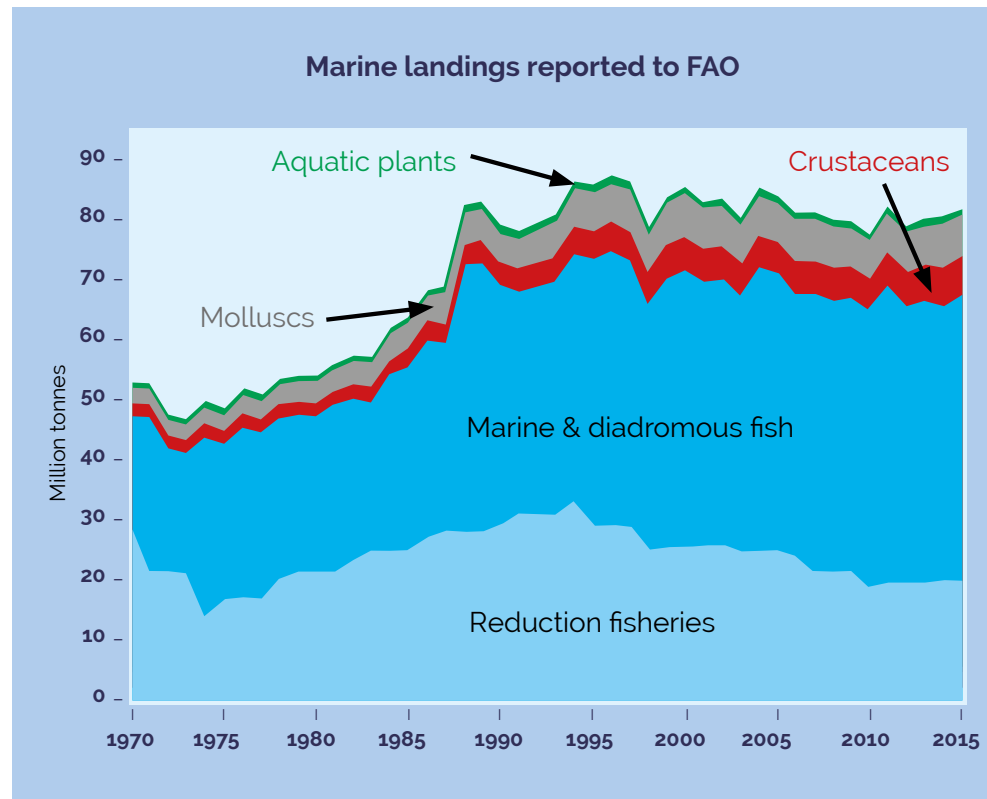


Figure 2A. (FAO, 2017b). Global marine landings and mariculture production. Reduction fisheries consist mostly of small pelagic plankton-feeding fish such as anchovies, sardines and herrings, which are processed into fishmeal and oil.

Mariculture production reported to FAO

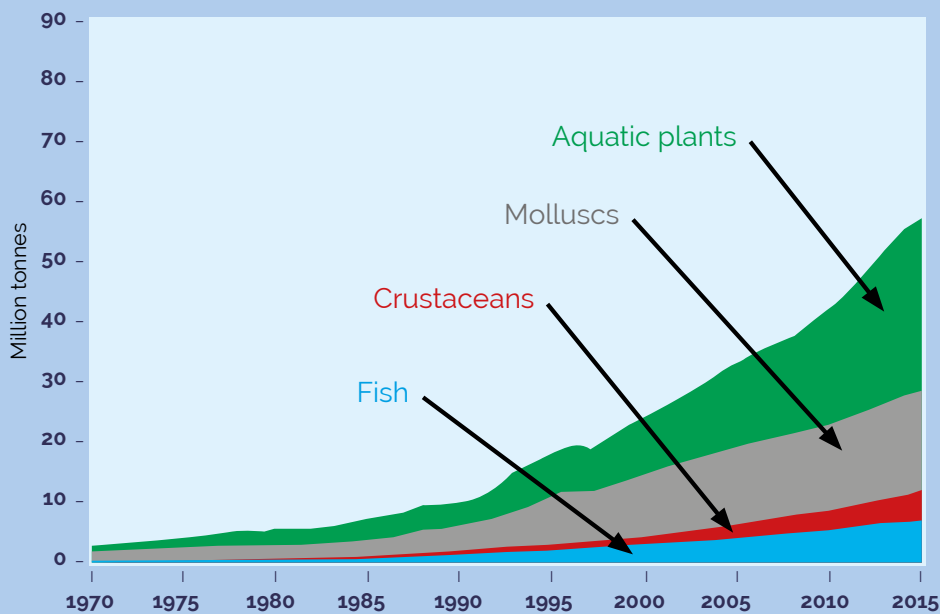


Figure 2B. (FAO, 2017b). Global marine landings and mariculture production. Mariculture of fish and crustaceans depends on feed that consists of fishmeal and oil and of land-based produce, such as corn and soybeans. Cultured molluscs and aquatic plants extract their nutritional requirements directly from the ocean and make up today more than 50% of all mariculture produce.

Landings of wild-caught marine (including diadromous fish) species reported to FAO are shown in Figure 2A. In 2015, total marine landings were 82 Mt and mariculture production (Figure 2B) amounted to 56 Mt.

While the total landings of wild species have been more or less constant since 1990 (Figure 2A), total mariculture production has been growing by 6.8% per year (estimated by applying an exponential function to the data for the period 1990 – 2015), with the highest growth rates for finfish (7.8%) and crustaceans (8.3%). In contrast to algae and bivalves, mariculture of finfish and crustaceans depends on the input of feed. About two-thirds of the fishmeal and 90% of the fish oil produced from reduction fisheries are subsequently used as feed for these species (Tacon, Hasan, & Metian, 2011). Reduction fisheries' outputs of meal and oil have dropped over the last decades and were about 20 Mt in 2015, whereas mariculture of finfish and crustaceans amounted to 11 Mt. Pelleted feeds include other major ingredients (such as soya and corn), alongside fishmeal and fish oil. An increasing fraction of terrestrial feed ingredients has facilitated the high annual growth rates observed in finfish and crustacean mariculture, despite the decrease in reduction fisheries (Figure 2A). However, the increasing terrestrial feed ingredients questions to what extent these groups should, in the context of this report, be classified as 'food from the oceans'.

Figure 3. Marine food per-capita, calculated as the sum of capture fisheries landings (excluding reduction fisheries) and mariculture production of fish, crustacean and molluscs, divided by the human population size (data from the FAO and UN).

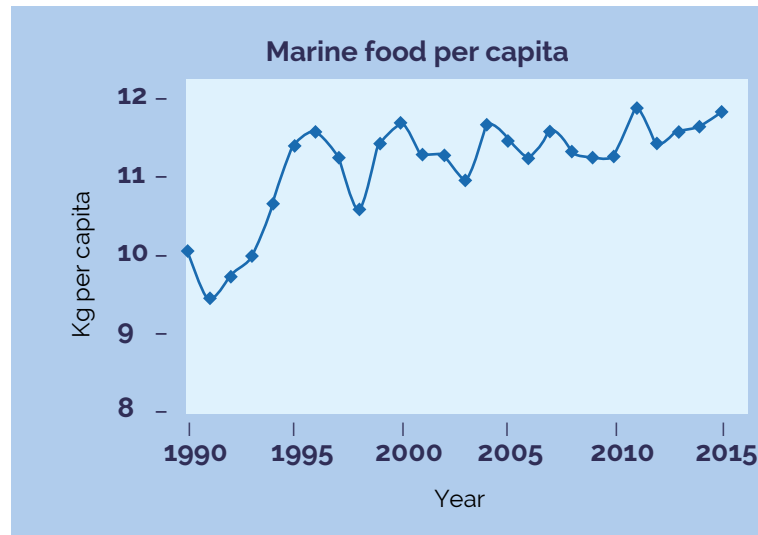


Figure 3 shows that marine food per-capita has been between 11-12 kg since 1999. This number differs from total fish provided per-capita, which includes freshwater species and was 20.1 kg in 2014 (FAO, 2016a). Note, however, that the amount actually consumed is less, due to wastes (see Section 3.1.2).

2.2 FAO AND WORLD BANK GROWTH PROJECTIONS FOR FISHERY AND AQUACULTURE

FAO (2016b) made a projection for fishery and aquaculture (i.e. including freshwater species) for 2025 that was based on expected trends in important drivers and based on ambitions to align future fishery and aquaculture with the 2030 Agenda for Sustainable Development (United Nations, 2015b). According to this projection, which did not report separate numbers for marine and inland production, total fish production will increase to 196 Mt by 2025, i.e. a growth of 29 Mt was projected, which corresponds to a growth rate of 1.5% per year. Nearly all this growth (28.5 Mt and 3% growth per year) originates from aquaculture, with the largest absolute growth in freshwater, which is expected to take place in developing countries.

For the EU, little aquaculture development is expected and stable capture fisheries are projected to make up the main amount (79%), also by 2025. The projected EU growth for total fish production is 2.3% for the outlook period. The demand for fish, however, is expected to rise, and it follows that so also will the imports, which are projected to increase by 16.9%.

The World Bank (2013) had a less optimistic outlook. The baseline scenario projected by it has been a total marine and freshwater fish supply of 187 Mt by 2030, which corresponds to a growth rate of 1.1% per year, i.e. not much higher than the projected population growth rate (United Nations, 2015a). The discrepancy between the FAO and World Bank outlooks is due to a lower projected growth in aquaculture by the World Bank. The reason for this is not clear, but different assumptions about price developments for fishmeal and oil, which are important ingredients in aquaculture feed, may be one factor.

From a biological point of view, the future growth potential of mariculture depends on whether the cultivated species depend on input from capture fisheries, or not. Stable capture fisheries, which are assumed in both projections, will obviously halt the production of mariculture species such as finfish that critically depend on feed input from this fishery, though not the production of species that are cultured independent of it (such as macroalgae and bivalves).

2.3 MAIN DRIVERS FOR INCREASED FOOD PRODUCTION

2.3.1 Human population growth and expectation of an increased human trophic level

The human population is projected to grow by 33%, from 7.3 to 9.7 billion in the period from 2015 to 2050 (United Nations, 2015a). This growth is unevenly distributed globally and most (97%) of it will take place in Africa (54%) and Asia (37%). Many countries in these regions, and in South America as well, are currently characterised by diets that are primarily plant-based, but where a larger future amount of meat and fish can be expected, along with economic growth and an emerging middle class (Kharas, 2010), implying an increased human trophic level (TL, see Box 1). A higher human TL puts additional pressure on the food system because feed must be produced to raise animals for human food and the conversion from feed to animal food is associated with a substantial loss of energy and biomass, in culture as well as in nature (Box 1).

Box 1. Trophic level, loss of energy, and ecological efficiency: Trophic level (TL) is an important term in ecology and can be defined as the position that an organism occupies in a food chain – what it eats, and what eats it. A TL equal to 1 corresponds to photosynthesizers (primary producers) such as plants and phytoplankton. The next levels are calculated according to diet. TL = 2 corresponds to herbivores that eat only plants or phytoplankton and TL = 3 to carnivores that eat only herbivores. However, most animal and human populations have mixed diets. A TL = 2.5 corresponds to a diet consisting of 50% plants and 50% of herbivores, or a diet of 75% plants and 25% carnivores eating herbivores. Marine predators high up in the food web, such as the killer whale, can have a TL higher than 5. The trophic level of species i (TL_i) can generally be estimated according to the following equation: $TL_i = 1 + j (F_j \times TL_j)$ where F_j is the fraction of a food organism of species i , TL_j is the trophic level of the food component and j is the number of feed organisms (Gascuel & Pauly, 2009).

Between each trophic level there is a substantial **loss of energy**, typically ranging between 80 and 97% for different ecosystems. An important discrepancy between agriculture and fishery is that the agriculture harvest is characterised by a low TL (i.e. dominated by plants), while the fishery harvest is characterized by a high TL (carnivorous fishes are targeted). The **ecological efficiency** of the global fishery catch is found by dividing it by the global primary production and is ~ 0.02% (EASAC, 2016). More food from the ocean can be produced if this efficiency can be increased in a sustainable way in fishery and mariculture (i.e. not including land-based aquaculture). Trophic level is an important term for assessing ecological efficiency for both wild-caught stocks and for cultured species. A high TL implies low ecological efficiency and a low TL implies high efficiency. There is considerable knowledge collected on the trophic level of marine animals.

Bonhommeau et al. (2013) report that average national human TLs vary between 2.04 (almost only plants in a diet) and 2.6 (a diet with more meat/fish). Similar to population growth, these TLs are unevenly distributed globally, with the low, but increasing human TLs in Asia and Africa. On average, the global human TL has increased over the last 50 years and was estimated to be 2.21 in 2010. This increase in TL reflects that meat and fish make up a larger part of the diet than previously. According to an analysis of socio-economic developmental indicators, a convergence of human TL of ~2.4 over time was found (Bonhommeau et al., 2013), which implies that a further increase in the proportion of meat and fish in the human diet in the coming decades will happen. The expectation of a continued rise in human TL, and the pressure on the sea this implies, is strengthened by today's nutrition challenges.

2.3.2 Nutrition challenges and nutrition security

Global nutrition challenges were summarised by the EASAC Working Group on Opportunities and Challenges for Research on Food and Nutrition Security and Agriculture in Europe (ter Meulen et al., EASAC, 2017, in preparation):

There are three sets of nutrition issues that exist in parallel and are partly connected: hunger and undernutrition, micronutrient deficiencies, and overnutrition with obesity. This represents a triple burden to public health and highlights the importance of nutrition security as well as food security (Horton and Lo, 2013). Increasing numbers of people are overweight or obese and many consume calorie-dense but nutrient-poor diets. [...] The [2015] UN Food and Agriculture Organization (FAO) assessment (FAO, 2015) [indicated that, at that time, about] 795 million people [were] chronically undernourished in terms of calorie deficit to meet energy needs to lead a healthy and active life. However, latest data from FAO indicate this number of hungry people is now rising again (FAO, 2017d). The number affected by caloric deficiency has decreased by about 20% in the past decade but an additional approximately two billion people suffer from undernutrition from micronutrient deficits. Data from the Global Hunger Index (von Grebmer et al., 2016) indicate significant progress in many countries in reducing calorie deficiency but less progress on child stunting and micronutrient deficiencies.

Hence, in addition to calories and protein, global food systems must supply sufficient amounts of important micronutrients such as iron, zinc, iodine, long chain omega-3 fatty acids and vitamins. Marine fish are crucial sources of these micronutrients, and scenarios of stable (FAO, 2016b) wild fish capture will, unless compensated by other nutrient sources, lead to increased micronutrient and essential fatty acid deficiencies for the human population (Golden et al., 2016). Today's undernutrition and micronutrient deficiency are likely to increase demand and put more pressure on seafood production than that implied by human population growth alone.

2.4 THE POTENTIAL FOR INNOVATION AND FUTURE 'GAME-CHANGERS' IN FISHERY AND MARICULTURE

The FAO outlook is primarily a 'business as usual' scenario, with a slight increase from capture fisheries (about 1%) due to assumed recovery of certain stocks, following improved management and enhanced utilisation of fishery production through reduced discards, waste and losses. It was also projected that the portion of capture fisheries used for direct human consumption will increase somewhat, due to an expected 1% decrease in fishmeal production. Such management and utilisation improvements are an important answer to the question, 'How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?' and are also addressed in the present report.

Radical innovations involving more fundamental changes in how we exploit the ocean will become important and are not accounted for in the scenarios presented in Section 2.2. One potential game-changer is to harvest the ocean with a higher ecological efficiency (see Box 1) than today, for example, by harvesting at lower TLs than in contemporary fishery and mariculture (Duarte et al., 2009; Bonhommeau et al., 2013; Olsen, 2015; EASAC, 2016).

Trophic level (TL)	Approximated maximum annual biological production in the ocean (wet weight)	
	Mt	Kg per capita
1 Primary production Phytoplankton (mainly) and macroalgae	500,000	70,000
2 Herbivores zooplankton (e.g. krill)	50,000	7,000
3 Carnivore 1 zooplankton/ mesopelagic fish/ forage fish	5,000	700
4 Carnivore 2 forage fish/ fish with high commercial value	500	70
5 Carnivore 3 fish with high commercial value	50	7
6 Carnivore 4	5	0.7

Table 1. The annual production at different trophic levels in the ocean, as approximated according to an ecological efficiency of 10% between each level (see Box 1), a global oceanic primary production of 50×10⁹ tonnes carbon, and a wet weight to carbon ratio of 10.

The substantial increase in the natural biological production that is associated with decreased TL is illustrated in Table 1. While the annual oceanic production at TL5 (such as wild salmon, cod and tuna) corresponds to 7 kg per capita, the annual oceanic primary production (TL1) amounts to 70,000 kg per capita (which is similar to the primary production on land). Due to the low transfer efficiency (around 10%) between successive TLs, eating from low TLs enables a higher potential harvest than eating at high TLs. Since today's seafood is currently harvesting at a relatively high TL (Figure 4), there exists a potential for increased harvest, addressed in this report.

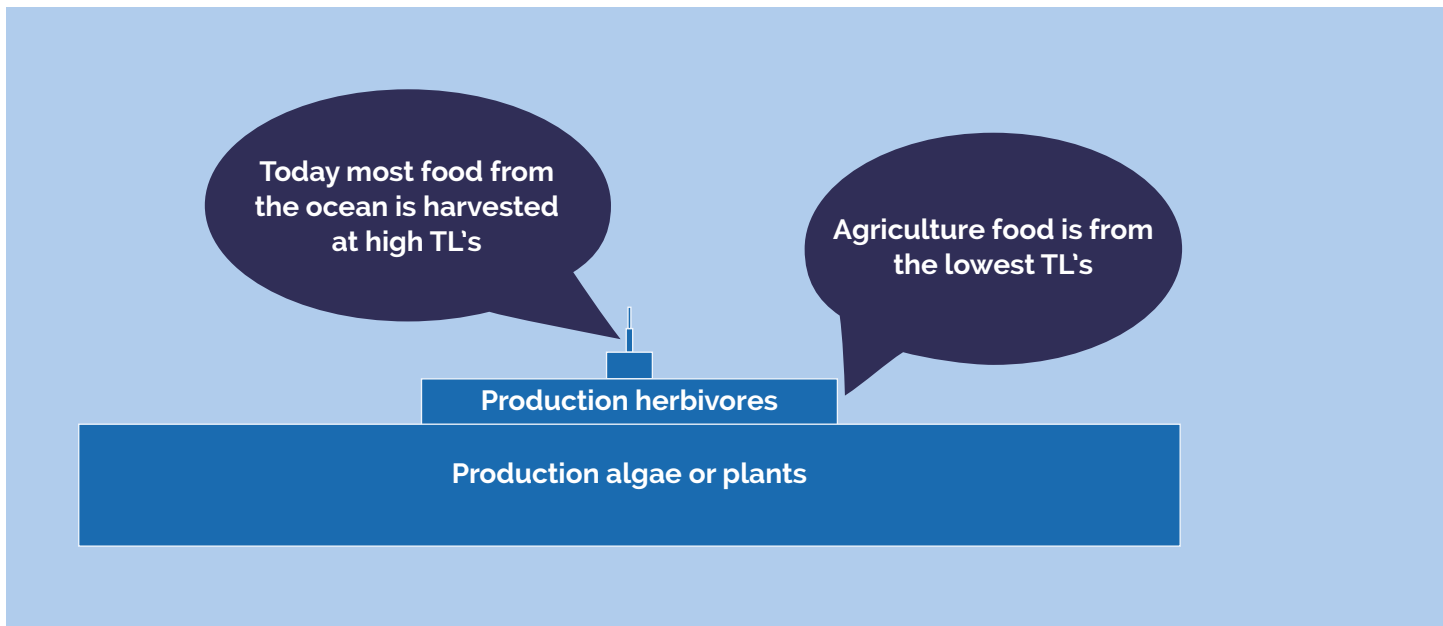


Figure 4. Illustration on how the natural production diminishes with increasing trophic level (TL). For each trophic level, the natural production is roughly 10% of that at the previous level. This is illustrated by the size of the areas, except for the highest TL (TL=5), which is enlarged in order to be seen.

3. The biological potential for an increased ocean harvest

3.1 HOW CAN MORE FOOD AND BIOMASS BE OBTAINED BY SUSTAINABLE HARVESTING OF WILD POPULATIONS?

Our oceans, the largest underexplored component of the Earth system, are also potentially home to a large number of resources not exploited or sub-optimally exploited currently, which could directly impact upon food security and the wellbeing of humanity. However, too extensive extraction of these resources might have repercussions for the outcome of the established fisheries, for biodiversity, and for the oceans' ability to sequester greenhouse gases, to name but a few.

With the performance of marine fisheries on wild fish, we are extracting food and biomass from a natural ecosystem that is impacted by fishing on a regional and global scale (Figure 5) (Pauly et al., 1998), as well as by climate change (Allison et al., 2009). The interplay between extraction by fisheries and the role of climate on population dynamics ultimately determines the biomass of wild fish stocks available for harvest.

Ultimately, production at higher trophic levels is limited by autotrophic production at the base of the food chain. Correlations between primary production and fish biomass (Ware & Thomson, 2005; Irigoien et al., 2014) suggest a causal link. However due to the complex interactions within the food web, the magnitude of fish production cannot

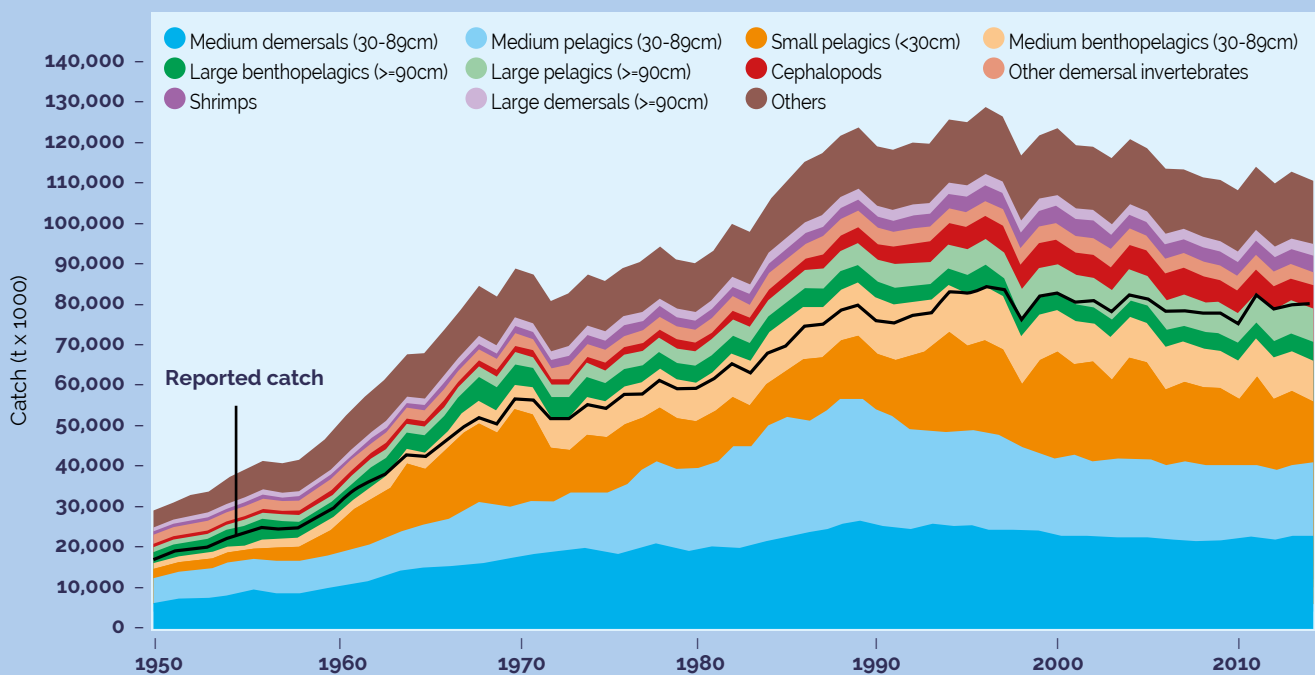


Figure 5. (Pauly & Zeller, 2015). Global marine catches with indications of major functional groups, based on an analysis that includes artisanal and unreported catches (see Pauly & Zeller, 2016). Note the overall decline of catches of about 1 Mt per year since 1995.

be directly linked to primary production, the reason being that primary production is transformed as it passes from prey to predator, with a loss at each trophic step and, as a result, fish production is rather weakly related to primary production because of variability in the number of trophic steps and in the transfer efficiency at each step.

The pursuit of maximum sustainable yield (MSY) of a fish stock is generally perceived as the proper objective to be gradually reached. MSY is, theoretically, the largest yield (or catch) that can be taken from a species' stock over an indefinite period, thereby maintaining a stable resource. Overfishing beyond MSY can cause depletion of target and non-target species, impacting upon marine populations and communities and changing the structure and function of marine ecosystems (e.g. Worm et al., 2006) and, as a result, their resilience. Opinions differ as to whether MSY should be the ultimate or an intermediate goal. Regardless, the difficulty (and necessity) of reaching MSY in mixed fisheries is a major impediment to the sustainable harvesting of targeted fish stocks.

Critically, maximum sustainable catches cannot be obtained from all species simultaneously, or from whole functional groups or trophic levels, or for individual species. This is because of changes in habitat quality and availability, climate variations and change, and because of resulting changes in trophic interactions and vital rates. The role of climate change on critical habitats for marine fish stocks, and the resultant implications for the extraction of biomass from stocks impacted, is clear (e.g. Cheung et al., 2009).

Due to trophic interactions and habitat variability, it is impossible to obtain MSY catches from all stocks simultaneously (e.g. Walters, Christensen, Martell, & Kitchell, 2005). Especially short-lived low TL species such as anchovies, herrings or sand eels need to be exploited well below the MSY level to prevent collapse and to stabilise ecosystems already impacted by fishing and climate change (Pikitch et al., 2012; Essington et al., 2015). Clearly, the MSY of an individual stock is a moving target, sensitive to climate impacts on habitats and the dynamics of interacting species in the system.

A number of options are presented in subsequent sections to increase the biomass available for human consumption. These options involve improved management, including the recognition of the role of climate on fish stock dynamics, reduction of waste resulting from bycatch and processing, as well as potential new sources of biomass stemming from underutilised sources. These options could, if taken advantage of, increase biomass for human consumption stemming from the marine environment, without jeopardising the future of these resources for future generations.

3.1.1 By improved sustainable management of existing fisheries

Biomass overfishing (i.e. reducing stock biomass to a level that impacts upon stock production) and climate change are influencing the productivity and structure of marine ecosystems, and are threatening the persistence of their resources for future generations. In order to preserve and optimally utilise these resources, and to enable an increase in the amount of food from wild species, there is a need for the establishment of robust management frameworks sensitive to climate variability and

capture fisheries. The establishment of estimates of maximum sustainable yield (MSY) to determine harvesting limits are a necessary first step (UNCLOS, 1982; UNFSA, 1995; European Union, 2013). It is the stated objective of the Common Fisheries Policy to rebuild stocks to levels capable of producing MSY, no later than 2020. However, official estimates for European waters indicate that 47% of 59 stocks with MSY assessments were subject to overfishing in 2014 and that in the Mediterranean and Black Sea, about 90% of the stocks were being overfished (European Commission, 2016; STECF, 2016).

Similarly, an independent recent analysis of 396 stocks in European and adjacent waters (from the Barents Sea to the Black Sea), found that about two-thirds of the stocks were subject to ongoing overfishing. About half of the stocks were outside safe biological limits, meaning that their biomass was so small that successful reproduction was endangered and catches were well below MSY (Froese et al., 2016a). The study also estimated that after rebuilding stocks above the level capable of producing MSY, as required by the Common Fisheries Policy (European Union, 2013), precautionary catches of 90% of MSY could increase yields by more than 50%, or about 5Mt.

Improved Management

A recent study (Costello et al., 2016) suggests that improved management could generate an annual increase in global fisheries of more than 16 Mt, relative to business as usual. They propose that with appropriate reforms, recovery can happen quickly, with the median fishery taking under 10 years to reach recovery targets.

However, evidence for rapid recovery of depleted stocks suggests that reductions in fishing pressure, although clearly necessary for population recovery, are often insufficient. Persistence and recovery are also influenced by life history, habitat alteration, changes to species assemblages, genetic responses to exploitation and reductions in population growth, due to depensation. Heightened extinction risks were highlighted recently when a Canadian population of Atlantic cod (*Gadus morhua*) was listed as endangered, on the basis of declines as high as 99.9% over 30 years (Hutchings & Reynolds, 2004). Clearly, the development of management frameworks sensitive to multispecies interactions and environmental constraints on population vital rates is necessary to optimally harvest marine fish populations, whilst preserving them for future generations.

Capture Size

Another measure, which would increase catches, is to optimise the length of the fish at first capture. For every level of fishing pressure, there is an optimum length at first capture that maximises the catch (Beverton & Holt, 1957). Currently, minimum conservation landing sizes in European fisheries are well below the optimum length, especially in large species such as cod or hake. The increase in catch that can be obtained by increasing the length at first capture to the optimum length depends on the difference between current and optimum length, but may be about 10% (Froese, Winker, Gascuel, Sumaila, & Paul, 2016b), i.e. more than 8 Mt globally and more than 1 Mt in Europe. An additional benefit of increasing the length at first capture is that

more juvenile fish are allowed to realise their growth potential and contribute to the next generation, which increases biomass, improves size structure and minimises the impact of fishing on the stock and on the ecosystem (Froese et al., 2016b).

Assessment

The most important obstacles to the implementation of improved management systems are that the majority of the exploited stocks in Europe, and globally, have no adequate assessment of the stocks, in particular in the light of changes in habitat distributions driven by climate change (e.g. Allison et al., 2005). An issue for the stocks that are assessed is that advisory and management systems operate with substantial delays in recording actual population changes. Management typically reacts slowly, and actions to decrease pressure on declining resources function with substantial delays. Slow responses tend to exacerbate naturally-occurring change, leading to greater losses in the yield of the declining populations. These delays have the potential to impact not only on food extraction, but also the resilience of the different stocks and hence the ecosystem.

In summary, technical and biological constraints include a lack of management systems that assure, with high probability, the continued functioning of the food web, given that humans are an 'invasive voracious predator'. There is a:

- Lack of adequate assessment and management systems for many stocks;
- Lack of a management framework sensitive to changes in the ecosystems supporting exploited marine resources (i.e. environmentally sensitive MSY, EMSY);
- 'Too little, too late' management actions to reduce fishing pressure if stocks are declining;
- Lack of enforcement; and
- Rebuilding of stocks requires reduced landings. However, given that reduced landings may not be sufficient due to, for example, changes in the ecosystem, early and adaptive management frameworks are urgently needed.

3.1.2 By reducing discards and increased utilisation of offals/discards

It is quite common that around one-quarter of the catch constitutes unwanted species or undersized fish, termed 'bycatch'. The magnitude of the bycatch problem was estimated in 2009 to constitute 40.4% (38.5 Mt) of the global marine catches at that time (Davies, Cripps, Nickson, & Porter, 2009). They defined bycatch as catch that is either unused or unmanaged. Part of the bycatch is landed and used, but the unused fraction is thrown back into the ocean as discards. Discards were estimated at 27 and 7 Mt per year in global studies conducted for FAO in the 1990s and 2000s respectively (Alverson, Freeberg, Pope, & Murawski, 1994; Kelleher, 2005) and at 10 Mt on average (for 2000 – 2010) by Pauly and Zeller (2016) (European Commission, 2011a).

Discarding of bycatch has been attributed to: (1) little or no commercial value for the bycatch, (2) the cost involved in landing fish, including sorting, storage, and processing

and (3) storage limitations in trawlers (Clucas, 1997). Some of the bycatch species survive this process while others die and are dumped in the environment, representing a wasted opportunity for biomass and food production. This is being tackled now within the EU, with the implementation of the Landing Obligation of the CFP.

After capture, the targeted fish species are gutted and the viscera thrown back into the ocean. Thus, an additional 10-20%, corresponding to 8-16 Mt of biomass, is lost in this step. Subsequently, during processing it is common that the utilisation factor is well below 50%, which corresponds to 33 Mt in 2015. Another one-third of what is processed is wasted during distribution and at the retail and consumer level (Love, Fry, Milli, & Neff, 2015) and corresponds to another 11 Mt in 2015. Clearly, the waste of viscera and the low utilisation efficiency in the processing link, as well as the potential utilisation of discarded species, together present opportunities to produce more food from marine capture fisheries, e.g. by turning these wastes into feed for mariculture of carnivores (see Section 3.2).

The above numbers suggest that the potential for utilisation of today's discard and wastes associated with the global capture fishery is significant. This level is higher than indicated by Béné et al. (2015) and the FAO (2016b). The FAO (2016b) reported that global fish losses (including discards) and waste amount to 35% of landings, which correspond to 29 Mt of a marine landing of 82 Mt in 2015.

It should be noted that some of the waste potential is already utilised, e.g. in industrial fish processing. 30–70 % of the fish ends up as by-products, e.g. heads, viscera and backbones (Olsen, Toppe, & Karunasagar, 2014). These by-products are usually further processed into fishmeal and fish oil, primarily used for feed purposes and indirectly contributing to food security (FAO, 2016b).

Technical and biological constraints for reducing discards that exist include the:

- Lack of selective fishing gear to reduce discarded bycatch;
- Lack of gentle fishing gear that increases the survival of the discarded bycatch;
- Lack of management systems aimed at reducing discarded bycatches.

Technical and biological constraints for utilising discards and offals include the:

- Capacity to store (on vessels), deliver and process discards and offals;
- Suitability for feed ingredients further down the value chain (i.e. food safety regulatory issues).

3.1.3 By harvesting wild species that are not, or only marginally exploited, today

Harvesting zooplankton

Zooplankton are organisms that span a range of sizes, from micro-meter (ciliates) to meter- scale (large jellyfish). A biomass of around 2,000 Mt has been estimated globally for the upper 200 meters in the ocean for the mesozooplankton of size 0.2 – 2 cm (Moriarty & O'Brien, 2013). The possibility of utilising plankton as a food source for

mankind has been discussed since the late 19th century, but only minor quantities (0.1 Mt per year) have been harvested (Omori, 1978). Very small quantities are also used as live feed for the early developmental stages of fish in mariculture (Blanda et al., 2017). Due to the shortage of fish oils, there is a renewed interest in harvesting zooplankton (Tiller, 2008). The Norwegian Directorate for Fisheries has, despite the ban against such fishery, recently proposed a plan for managing a precautionary trial fishery on a zooplankton species, *Calanus finmarchicus* (Fiskeridirektoratet, 2017). Out of an estimated biomass of 33 Mt in the Norwegian Sea, a precautionary quota of 0.165 Mt has been proposed within the Norwegian EEZ (Exclusive Economic Zone). While this quota, (0.5%), might appear low for a short-lived species (<1 year), it accounts for the fact that fishery will not take place evenly over the entire distributional area, but would be localised and thereby with higher local exploitation rates. Also, there are large no-take zones, to avoid bycatches of fish larvae.

Fishery on Antarctic krill (*Euphausia superba*)

Fishery of Antarctic krill began in the 1970s, but there have been substantial changes in its size and operation over the last 40 years (Nicol & Foster, 2016). Krill in the Southern Ocean constitutes the main diet for most of the marine predators there (penguins, seals, whales and fish). Krill are one of the most abundant invertebrate species on the planet, with a biomass of the order of 100 Mt (Atkinson, Siegel, Pakhomov, Jessopp, & Loeb, 2009; Siegel & Watkins, 2016). They are a major grazer of primary production in the system, serving a key role by converting primary production into biomass for higher trophic levels, thereby acting as a 'keystone species' in the Southern Ocean ecosystem (e.g. Flores et al., 2012).

Management of the krill fishery is implemented, under an international treaty, by the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR). The ecosystem-based principles of CCAMLR (CCAMLR, 2017) require that not only should the krill fishery be sustainable, but also that account must be taken of the species that depend on krill for food and of the wider ecosystem impact of its fishing. Current catch levels, which are around 0.3 Mt, are low compared to the precautionary catch limits of 5.61 Mt for the area where the fishery now operates (across the Scotia Sea and around the Antarctic Peninsula) and 8.6 Mt for the whole of the Southern Ocean. This suggests a potentially large underexploited resource, which could provide >10% (by mass) of all current global marine landings (Grant, Hill, Trathan, & Murphy, 2013). There are major gaps in understanding, especially to assess whether it is possible to remove large amounts of krill from the Southern Ocean ecosystem. Consequently, there are currently interim measures in place that restrict fishery expansion and additional measures that control the development of new fisheries.

Today's biological and technical constraints for harvesting more zooplankton include:

- A lack of harvesting methodology, leading to high energy costs for harvesting, in particular, for organism sizes smaller than krill;

- Fishing bans and precautionary approaches that are applied in order not to reduce the outcome of traditional fisheries and avoid risk of changing ecosystem functioning.

Harvesting mesopelagic fishes

In the FAO's search for unexploited fishery resources, a global estimate of ~1,000 Mt mesopelagic fish living in the upper 1000 meters was suggested (Gjøsaeter & Kawaguchi, 1980). These fishes feed on zooplankton, and their trophic position compares to commercially-exploited fish species like sprat, herring and mackerel. The above abundance estimate was considered to be conservative, and a recent study suggests that the biomass might be closer to 10,000 Mt (Irigoien et al., 2014), which has attracted renewed attention to the utilisation of mesopelagic fishes. However, the actual biomass level is uncertain, due to inadequate sampling methodology (Kaartvedt, Staby, & Aksnes, 2012) and challenges associated with acoustic measurements (Irigoien et al., 2014). If we are able to exploit these fishes at sustainable levels without impacting upon biodiversity (Robison, 2009) and compromising the oceans' ability to sequester carbon (Davison, Checkley, Koslow, & Barlow, 2013), we could produce more food and potentially many new nutraceutical products (Lea, Nichols, & Wilson, 2002).

If the mesopelagic biomass represented just one species and a MSY-based management approach were applied, the potential harvest would be higher than 100 Mt. However, the situation is more complicated, because mesopelagic fishes consist of a large number of species with unknown population structure and a complex biogeography (Proud, Cox, & Brierley, 2017). Furthermore, similar to Antarctic krill in the Southern Ocean, the mesopelagic fishes appear to be an important component of the large tropical and temperate oceanic ecosystems (Irigoien et al., 2014) which, at least on the shorter time horizon, calls for a precautionary approach, i.e. harvesting far below MSY. Clearly, sustainable exploitation of the mesopelagic fish community represents a potential game-changer in the production of food from marine sources. However, this requires that catch, fishing effort, processing and related challenges would double – quadruple, compared to current levels. Also, in order to avoid local depletions and disruption to ecosystem functions, fishing needs to be distributed evenly over large ocean areas. Due to current biological and technical constraints, it is hard to see that a sustainable and viable mesopelagic fishery can be developed in the near future. Recent studies indeed demonstrated that trawling in the deep-sea determined the desertification of the seafloor (Pusceddu et al., 2014). Limited and strongly-regulated precautionary trial fisheries appear more realistic.

Today's biological and technical constraints for realisation of the potential include a:

- Lack of fundamental biological knowledge (such as species composition, abundance, spatial distribution and vital rates of the species) that is needed for sustainable resource management;
- Lack of adequate sampling and harvesting methodology for exploration and exploitation.

3.1.4 By harvesting wild stocks of macroalgae

Harvesting wild stocks of macroalgae, currently around 1 Mt (FAO, 2014), affords income generation for human food products with perceived health and medical benefits, as well as for horticultural and agricultural applications, for alginates and for cosmetics. The largest abundances of macroalgae are in temperate regions, where they are attached to shallow rocky bottoms where sunlight is sufficient for photosynthesis. Here, seaweed and kelp beds make up an important habitat for other organisms and sustainable harvesting needs to take this into account. Small-scale (i.e. artisanal) hand-cutting or picking of wild seaweed is regarded generally as sustainable (Rebours et al., 2014; Scottish Government, 2016). Large-scale (i.e. industrial) mechanised harvesting of seaweeds is costly, unselective, and prone to contaminate native stocks. Mechanised harvesting methods able to cut at varying depths are now in use. However, compared to more traditional manual methods, significant numbers of small fish, invertebrates and amphibians are often collected and killed by the harvester. Plant fragments increase the spread of invasive plant species or accumulate and decompose on shorelines. It has become obsolete in some areas for ecological and cost reasons (Bixler & Porse, 2011; Rebours et al., 2014). According to a Norwegian study on kelp harvesting, mechanical harvesting can be successfully implemented, with a harvest plan based on a clear understanding of ecology, life cycle and ecosystem and regular review. This would take into account storm frequency, hot water events, continued warming of waters and changes in herbivore populations associated with the beds (Vea & Ask, 2011). How much more food and biomass that can be harvested globally in this way, however, is uncertain.

Today's biological and technical constraints include:

- Concerns for the negative effects of harvesting on the habitat and biodiversity associated with seaweed and kelp beds;
- Public acceptance of harvesting.

3.1.5 By redirecting reduction fisheries to direct human consumption

About 20 Mt of global catches are being reduced to fishmeal and oil for use in processed feed (e.g. pellets), or put to other uses such as direct feed, bait fish, pet food, or fertilizer (FAO, 2016). Some of the feed is used for indirect human consumption through farmed fish, chicken or pigs, but this comes with an unavoidable loss of ocean-derived protein (Wijkström, 2012).

Over 90% of reduction fisheries catch consists of species that are fit for direct human consumption (Cashion, Le Manach, Zeller, & Pauly, 2017), with many of them (anchoveta, sardine, herring, sprat, capelin, mackerel, sand eel, Norway pout, blue whiting and others) already being consumed on a regular basis and with an increasing trend (WBGU, 2013).

In Asia, Africa, the Pacific Islands and other regions of the world, the consumption of forage fish has a long tradition and is a major source of protein in poorer coastal

communities (Noone et al., 2012). The increase in demand for and prices of forage fish has worsened the access to affordable fish for poor population groups in some regions (WBGU, 2013). For example, in the Philippines, so-called trash fish which were a cheap protein source for the poor are used for direct feed in grouper aquaculture (Ottolenghi, Silvestri, Giordano, Lovatelli, & New, 2004) and in Vietnam, prices for trash fish are increasing because of demand by *Pangasius* catfish farms (Funge-Smith, Lindebo, & Staples, 2005).

In European waters, recent catches of forage fish and other species that are used for non-food products total over 5.8 Mt, with most of these stocks exploited at or above maximum sustainable levels (Froese et al., 2016b). In the EU, about 3.3 Mt of forage fish are reduced to non-food use (Failler, van de Walle, Lecrivain, Himbes, & Lewins, 2007). The countries with the largest reduction fisheries are Denmark, Norway and Iceland (Cashion, 2016). In 2015, Europe imported 841 thousand tonnes of non-food use fish products (EUMOFA, 2016), representing about 8 Mt of forage fish (if a 1:10 dry to wet weight conversion ratio is assumed). In comparison, the EU aquaculture sector produced 1.6 Mt in 2014 (STECF, 2016).

A recent trend in the species composition of reduction fisheries is a decrease in traditional species, such as anchoveta, sardine and herring, and an increase in species that have not been fished previously and that are often not even identified to the species level (Cashion et al., 2017). Such indiscriminate 'biomass fishing' is seen as a threat to the stability of marine ecosystems and to the abundance of high-value/high-TL species (e.g. cod and tuna), which depend on low trophic-level biomass for sustenance (Funge-Smith et al., 2005; Alder, Campbell, Karpouzi, Kaschner, & Pauly, 2008; Pikitch et al., 2012).

In conclusion, a substantial and rapid increase of affordable food from the ocean is achievable by redirecting more reduction fisheries towards direct human consumption. Note that there is, however, no scope for expanding fisheries on forage fish because most are already fully-exploited or over-exploited. Ecosystem-based management demands that these species, which often play a key role in the energy transfer to upper trophic levels, are exploited well below maximum sustainable yields to ensure stable ecosystems and the availability of a wide variety of seafood for future generations.

Today's biological and technical constraints include:

- Competing demand for the production of fishmeal and oil; and
- Resistance to fish these species below MSY levels.

3.2 HOW CAN MORE FOOD AND BIOMASS BE OBTAINED BY SUSTAINABLE MARICULTURE?

Background and concepts

The low ecological efficiency of the capture fishery harvest is a main constraint to increasing food yields from traditional fisheries (i.e. the harvest as a fraction of the primary

production underlying the harvest, see Box 1). It is, however, possible to increase the efficiency of mariculture beyond that of fisheries and to obtain more food and biomass by sustainable mariculture. This is because cultivation allows the selection of species to be cultured in a way that the ecological efficiency of the mariculture harvest can be increased by cultivation of organisms of lower TLs (see Box 1) and by transforming high TL carnivores to low TL carnivores by use of appropriate feed composition.

Groups of organisms that extract their nutrients from seawater, such as molluscs and macroalgae (see below), are low in the food chain and their ecological efficiency is correspondingly high. These groups face no biological growth constraints for increased cultivation generally, and could go far beyond today's production. Other groups, such as fish and crustaceans, need to be fed, but these groups include the most attractive and simultaneously high-cost aquaculture products (FAO, 2017c). A further increase in the production of these groups may face more serious growth constraints, such as shortage of crucial feed ingredients. This is already a threat for the coming decade and beyond. To counteract this, it is important to consider the fundamental mechanisms of these growth constraints.

Similar to capture fisheries, knowledge about the fate of marine primary production in the ocean and the inherent inefficiency of the traditional seafood chain, as compared to the agriculture food chain, is instrumental for analysing the potential of mariculture (Duarte et al., 2009, and below). This is also important to be able to establish a general strategy for developing sustainable mariculture. The primary production of the terrestrial and marine hemispheres are of the same magnitude (around 50 Gt C yr⁻¹, Field, Behrenfeld, Randerson, & Falkowski, 1998), and microalgae that are efficiently grazed and passed up in the food chain dominate marine primary production in the sea. The availability of the terrestrial primary production (which includes trees, grass and other plant food), is less directly available in the food chain. It is therefore a paradox, pointed out by Duarte et al. (2009), that only around 1.6% of human food (by weight basis) comes from the ocean, via fisheries and mariculture.

The low production efficiency of many fish (and crustacean) species, now named as marine carnivores (meat-eaters), is a consequence of the long food chains in the sea and the pattern of energy transfer in food chains. Humans globally feed, on average, at trophic level 2.21 (see Introduction), with some variation for different regions of the world (2.04-2.57, Bonhommeau et al., 2013). Plants and herbivore animals (grass-eating) in agriculture, constitute, on average, 98% of human food, while only the remaining 1.6% comes from the ocean (seafood chain). Among the food components taken from the sea, humans eat relatively small amounts of algae and herbivore animals, whereas carnivores from the sea are the main components of the eaten seafood globally. These carnivore animals are economically and nutritionally important and attractive groups produced in mariculture.

It can be deduced that humans feed around two steps higher in the seafood chain than in the agricultural food chain (Duarte et al., 2009; Olsen, 2015). Around 99% of the marine primary production is therefore lost, because of these two extra steps in the

current food chain, compared to the agricultural food chain. With this pattern, it follows that some 1% is left, which roughly corresponds to the fraction of food that comes from fisheries and aquaculture (1.6%). One main option to increase food production by mariculture is therefore to reduce the number of trophic steps compared to that of wild stocks in the sea and, by doing this, utilise the underlying primary production more efficiently. The only way to achieve this in capture fishery is to harvest at lower trophic levels, which is controversial (see Section 3.1.3).

In mariculture, there are two options. First, more food and biomass from the ocean can be obtained by increased cultivation of primary producers (i.e. TL1, e.g. seaweed) and herbivores (TL2, e.g. bivalves). This would compare to agricultural production, except that naturally low TL mariculture is independent of industrial fertilizers, feed and large supplies of freshwater. Second, fish that are high up in the food chain in nature can be brought down several trophic levels in mariculture, by feeding them with ingredients from low trophic levels, as has been done in salmon farming, for example.

Mariculture is a relatively new industry and it lags behind agriculture developmentally by 10,000 years (Duarte, Marbá, & Holmer, 2007). Great progress has, however, been made for many species. The mariculture sector faces many challenges, including technology, knowledge on nutrition and health aspects of cultured species, lack of breeding programmes, environmental interaction, access to coastal space, political and regulatory constraints, and lack of management routines in many countries. Gentry et al. (2017) have analysed the available coastal and ocean space that is suitable for mariculture, and find that vast areas are available for mariculture in most coastal countries and that this presents opportunities for countries to develop mariculture in line with their economic, environmental and social objectives. They mention "*restrictive regulatory regimes, high costs, economic uncertainties, lack of investment capital, competition and limitation on knowledge transfer into new regions*" as frequently cited reasons for the slow development of mariculture. An earlier, although broader, study by FAO yielded similar conclusions (summarised by Lovatelli et al., 2013). The conclusion of Gentry et al. (2017) is highly representative for all types of mariculture (see Section 3.2.2), but an additional potential constraint for mariculture of marine carnivore fish and crustaceans is access to new feed resources with long chain n-3 (LC n-3) fatty acids. Recent progress has been made in the efforts to derive new LC n-3 resources for mariculture (see section 3.2.6). Such feed resources have traditionally been obtained from fisheries, but landings have levelled off and the traditional fisheries cannot provide new resources to support the sustainable expansion of mariculture production for the decades to come.

There is no similar shortage in feed ingredients for cattle, pigs and chicken in agriculture, but this is because agriculture does not produce carnivore animals. Carnivore fish and crustaceans have a higher requirement for long-chain n-3 fatty acids (LC n-3) in their food than other animals, and these lipids have been taken from marine resources as fishmeal and fish oil (Tacon & Metian, 2008). LC n-3 rich fishmeal is used in all intensive fish culture (Tacon & Metian, 2008), as well as pig and chicken farming.

To overcome the shortage in LC n-3 rich feed resources, the fraction of marine ingredients in pelleted fish and shrimp feed has been gradually reduced during the last 10-15 years, and is now as low as 18-21% of dry pelleted feed for Atlantic salmon (Figure 6; Marine Harvest, 2017). Research undertaken in the EU-funded project 'ARRAINA' (ARRAINA, 2013) has shown that similar reductions are also done with success in other pure marine fish species, such as European seabass and gilthead seabream.

Resources from agriculture have replaced the resources from capture fisheries and filled the 79-82% gap (Figure 6). Modern mariculture uses pelleted feeds developed over time through extensive R&D programmes and delivered by large feed companies, securing high conversion efficiencies and low environmental footprints (see below). The development towards increased use of terrestrial feed puts pressure on agriculture and it can be questioned to what degree this food originates from the ocean (see definition Section 2.1). However, the cultured animal is marine and the production takes place in marine and brackish water. Moreover, if the terrestrial plant material of the feed could be substituted with marine plant and herbivore material, which also contain LC n-3, the pressure on agriculture would be released and more fish could be produced independently of fisheries on forage fish.

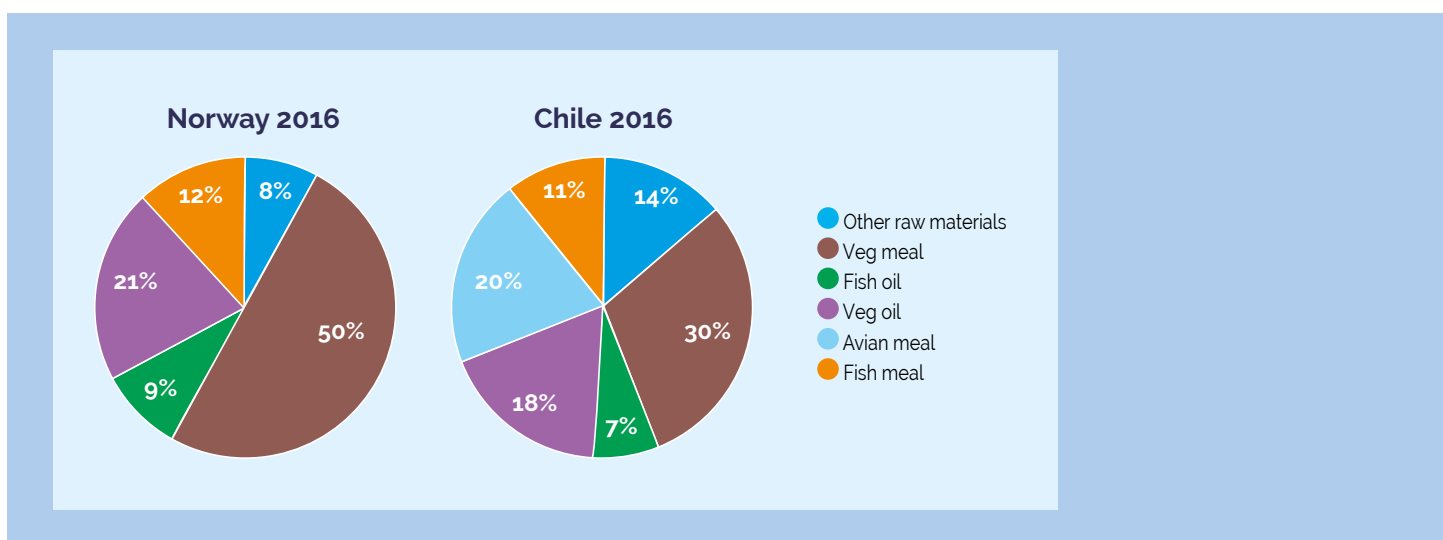


Figure 6. Fractions of main resources in salmon feed in 2016. Current inclusion of fisheries-derived feedstuffs, such as fishmeal and fish oil, are between 18-21%. The pelleted feed used for other marine fishes is similar to that of Atlantic salmon.

As noted above, molluscs and macroalgae are at the bottom of the food chain and extract their feed and nutrients directly from the sea (extracting mariculture). These groups therefore have a large biological potential for contributing to the challenge of obtaining more food and biomass from the ocean.

3.2.1 General strategy for increasing mariculture

The UN agency for food security (FAO) publishes comprehensive statistics on farmed species and assigns them to four main groups: 'marine plants' (named macroalgae), 'molluscs', 'fish' and 'crustaceans'. A general strategy for increasing production yields of food from the ocean via mariculture, whilst not compromising food quality and

the marine environment and with a potential future limitation in feed resources for carnivore animals in mind, could be as follows:

Strategy 1: Produce more organisms low in the food chain

- Macroalgae (by the FAO termed 'marine plants');
- Molluscs (among them are many shellfish species that are attractive seafood).

Strategy 2: Move farmed 'carnivores' down in the food chain

- By using more feed resources from lower trophic levels;
- Thereby using less fishmeal and fish oil.

Strategy 3: Derive new LC n-3 rich lipid sources

- New captured marine resources and waste, such as discards and offals from fishery and mariculture processing, zooplankton and mesopelagic fish;
- Cultured resources, such as single cell biomass of cultured thraustochytrids and suitable marine microalgae, cultured macroalgae, transgenic higher plants that produce LC-n-3 fatty acids and cultured marine animals, such as molluscs and other filter feeders.

As shown below, there is already a faster increase in the production of macroalgae and molluscs than of marine carnivores globally, and this development is expected to continue (Strategy 1). Macroalgae is a new product in most Western countries, but its culture and use is well established in many Asian countries, e.g. China, Japan and Korea.

The use of marine ingredients in pelleted feed for the most important farmed carnivores has been reduced gradually over the past 15 years, and these carnivores are now produced more than one TL lower than the wild stocks (Strategy 2, and see below), which implies that a more than ten times higher ecological efficiency has been obtained. Further independence of fish oil and meal originating from current reduction fisheries requires new and sustainable LC n-3 sources (Strategy 3). Comprehensive research activities have already been launched to establish new cultured sources of LC-n-3 rich lipids (Usher et al. 2017) and protein, including the previously-mentioned EU-funded project 'ARRAINA'. Other LC n-3 resources could be obtained from discards and waste from fisheries, and from increased catches of mesopelagic fish, krill and other zooplankton species (see Section 3.1).

3.2.2 Global mariculture production

The cultured production of molluscs and aquatic plants (macroalgae) exceeded the wild catches of these groups in 2015, whereas catches of crustaceans, finfish and other aquatic invertebrates still exceeded the cultured production of them (Table 1). The total production of marine organisms was 139 Mt, of which 41% was cultured.

Marine production, 2015	Capture	Culture
Crustaceans	6 063 118	4 494 725
Aquatic Invertebrates	559 067	387 456
Molluscs	7 105 975	16 187 570
Finfish	67 451 119	6 810 121
Aquatic Plants	1 088 162	29 273 392
	82 267 442	57 153 264

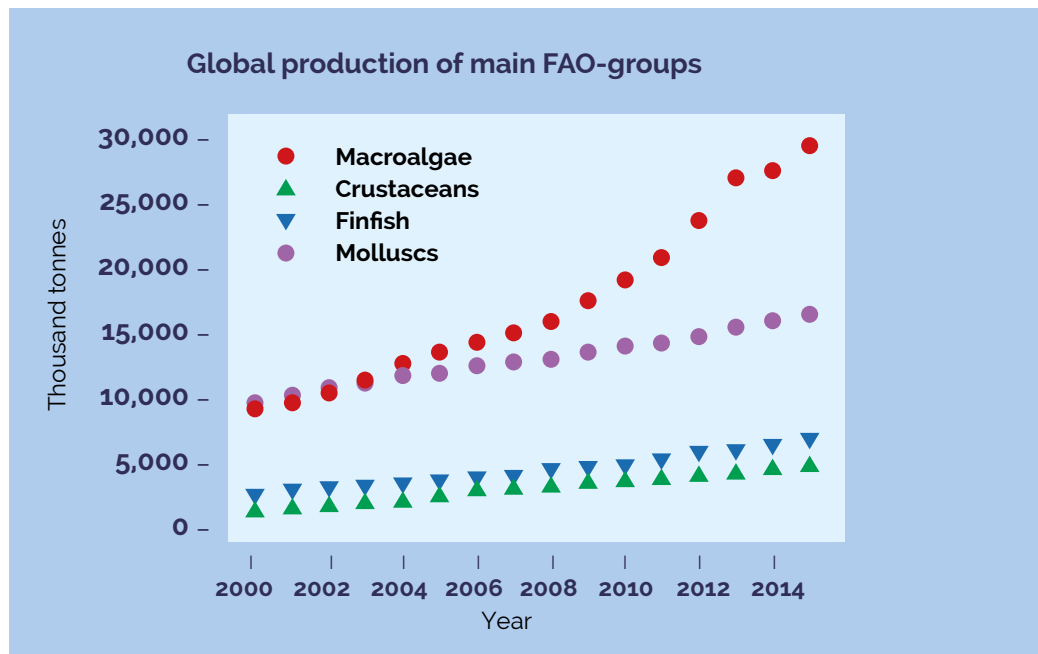
Table 2. (FAO databases). Comparison of captured and cultured main groups of marine organisms.

FAO databases inform that the global production in mariculture has developed steadily in recent decades (Figure 7). Most of this production takes place in marine waters, but the majority of the crustaceans (shrimp) are produced in land-based tropical coastal ponds and in brackish waters (here termed 'marine'). The production of animal products in aquaculture and fisheries is currently lower, but of same order of magnitude to that in agriculture (Figure 8).

As commented above, macroalgae (marine plants) exhibit the largest production volumes over the last 15 years in marine waters (Table 2, Figure 7). Molluscs show the second highest production volume and a steady rate of increase. As compared to Strategy 1, a substantial increase in mollusc and seaweed production has already taken place and might be accelerated from a biological point of view. The production volumes of fish and crustaceans, mainly shrimps, in feeding mariculture are lower, but the annual growth rate is higher than for macroalgae and molluscs.

The diversity of the cultured species is high within all groups (Duarte, Wu, Xiao, Bruhn, & Krause-Jensen, 2007; Olsen, 2011), but one or a few species are clearly dominant within these four groups of organisms (see below).

Figure 7. Global mariculture production of FAO groups of organisms in brackish and marine waters. Data taken from FAO (2017c).



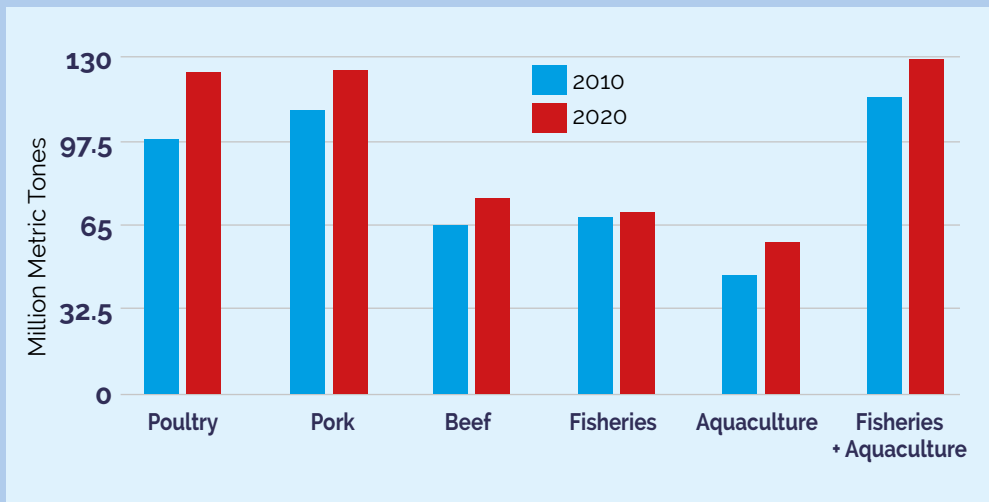


Figure 8. A comparison of meat production in agriculture with aquaculture and fisheries. Taken in the context of animal products available as human food, the OECD (2012) analysis predicts that the increase in aquaculture production will lead to a situation where the volume of total fishery production will exceed that of beef, pork or poultry, taken individually at some future stage.* Redrawn from OECD/FAO (2012) (*Beef and pork on a dressed weight basis; poultry and fish on an eviscerated basis)

3.2.3 Macroalgae and microalgae culture

Algal culture is the fastest-growing component of global food production at the moment (Figure 7) and is carried out in around 50 countries, especially China, the Republic of Korea, Indonesia, the Philippines and Japan (Duarte et al., 2017; Cottier-Cook et al., 2016; Loureiro, Gachon, & Rebours, 2015). In 2014, China alone produced 12.8 Mt of seaweed, constituting 54% of total global production (FAO, 2015; Cottier-Cook et al., 2016). Approximately 83% of this biomass is produced for human consumption (Loureiro, Gachon, & Rebours, 2015). Microalgae are also cultivated for foods and food additives (Enzing, Ploeg, Barbosa, & Sijtsma, 2014; Chacón-Lee & González-Mariño, 2010; Wells et al., 2017; FAO, 2014). The production of microalgae from cultivation is poorly reflected in available aquaculture statistics worldwide and significantly understated in the FAO's global statistics (FAO, 2016b), but production of the 'top three' microalgae – *Chlorella*, *Spirulina* and *Dunaliella* is relatively small, about 0.02 Mt dry weight per annum (Enzing et al., 2014).

Figure 9. (Xiao et al., 2017, licensed under CC-BY 4.0). Satellite Gao-Fen 2 image of the coastal area of Cangnan County, Zhejiang province, southeast China, showing large-scale seaweed (*Pyropia*) mariculture farms. SuperMap GIS 8 C (Supermap, 2017) was used to generate this map.



The traditional cultivation technology for macroalgae requires minimal capital investment and it has been relatively successful (Xiugeng, Ying, & Shan, 1999). Juvenile macroalgal cultivation is followed by on-growing in landbased tanks, intertidal zones, offshore deepsea and nearshore (Milledge & Harvey, 2016). Only a few species of macroalgae are cultivated successfully. In 2015, these were *Kappaphycus alvarezii*, *Eucheuma* spp., *Saccharina japonica*, *Gracilaria* species, *Undaria pinnatifida* and *Pyropia* (formerly *Porphyra*) species. In 2008, these species represented 76% of the total tonnage (Roesijadi, Jones, Snowden-Swan, & Zhu, 2010). In 2015, despite effort in algae breeding programmes, they still accounted for approximately 46% of total tonnage (FAO, 2017c).

China, in particular, has developed seaweed breeding programmes since the 1950s and more than 20 commercial varieties of *Saccharina japonica* have been developed, with improved yield, quality, disease resistance or stress tolerance (Zhang et al., 2007). Macroalgal cultivation is currently limited primarily to nearshore systems, using long line structures supported by buoys and connected to the main growing line, but the production may also extend to more open waters (Figure 9). Each system is optimised for the particular seaweed species being grown, including light availability and water clarity. Mechanised harvesting methods able to cut at varying depths are now in use but, compared to more traditional manual methods, significant numbers of small fish, invertebrates and amphibians are often collected and killed by the harvester. Plant fragments increase the spread of invasive plant species or they accumulate and decompose on shorelines.

Microalgae are also cultivated for foods and food additives (Enzing et al., 2014; Chacón-Lee & González-Mariño, 2010; Wells et al., 2017; FAO, 2016b). Intensive cultivation of microalgae is carried out either in open pond raceways requiring innovative solutions to deliver high all-year-round productivity at low cost, or in more controllable but, at the same time, more expensive contained photobioreactors.

Biological potential for harvesting more algae

Consumption of both macroalgae and microalgae is currently underdeveloped, especially in Western countries. However, there is a growing global demand for edible seaweeds that are contaminant-free, with a high level of traceability, and for microalgal culture (for oil). Most macroalgal production is for human consumption. The large-scale microalgae production facilities in Asia, India, Israel and Australia and the USA, that were initially established for biofuel, have mostly switched focus to make higher-margin products, food additives such as β -carotene, astaxanthin and polyunsaturated fatty acids.

Although macroalgae contain too few available calories via human digestion for complete nutrition (see below), the soluble component of the fibre in macroalgae, 20-75% in the total dietary fibre, is unusually high and offers health benefits (Gómez-Ordóñez, Jiménez-Escrig, & Rupérez, 2010; Cornish, Critchley, & Mouritsen, 2015; Wells et al., 2017). In contrast, microalgal carbohydrates, found in the form of starch, cellulose, sugars and other polysaccharides, have good overall digestibility and few limitations on their uses and applications (Chacón-Lee & González-Mariño, 2010).

Macroalgal protein is comparable to vegetable protein in essential amino acid composition, meeting FAO requirements and with an acceptable level of digestibility (78–89%), provided the seaweed is processed first (Bleakley & Hayes, 2017). Brown seaweeds contain 3%–16% protein, and both red and green seaweeds have higher levels (>50%) (MacArtain, Gill, Brooks, Campbell, & Rowland, 2007). Microalgal protein has a similar digestibility to that of seaweed (76%–88%) and compares favourably to egg, with a digestibility coefficient of 94.2%. The high protein content and favourable essential amino acid profile make both macro and microalgae a promising source of protein for humans and for cultured animals that could be more frequently used.

Macroalgae are low in lipids (0.3%–6%) compared to those in microalgae, which can be as high as 85% of their dry weight, depending on species, physical conditions and available nutrients. The most important lipids in microalgae are those with essential polyunsaturated n-3 fatty acids (PUFAs), such as linoleic- (LA), eicosapentaenoic- (EPA) and docosahexaenoic acid (DHA). Animals, including humans can, with limited capacity, synthesise EPA and DHA through elongation and desaturation of the shorter LA, but are not capable of introducing the n-3 double bond in LA, which therefore are essential nutrients for animals. Microalgae are the primary sources of DHA and EPA for zooplankton, fish and other multicellular organisms, and these essential fatty acids may become increasingly concentrated up the food web (MacArtain et al., 2007; Dawczynski, Schubert, & Jahreis, 2007; Wells et al., 2017).

Fucosterol occurs in many algae, especially red and brown macroalgae (Pereira et al., 2017), and this compound may have value in treating complications of diabetes and hypertension, as well as other major health concerns (Abdul, Choi, Jung, & Choi, 2016). Seaweeds are also rich in minerals (Pereira, 2011), with ash content ranging from 3.5–46%. Dried seaweed is being used as a salt replacement, reducing overall salt intake and increasing intake of other essential minerals (Lee, 2011). Seaweed is also a rich source of iodine and *S. japonica* has been used in China for centuries as a dietary iodine supplement (Holdt & Kraan, 2011). A relatively small amount of seaweed in a portion of a food would be required to allow it to become a 'good source' of iodine and allow its associated health benefits to be noted on packaging under EU (1924/2006) Approved Health Claims regulations (Rose, 2013). Japanese that traditionally have seaweed as a part of the diet have an average consumption 5–10 g dry weight of a mixture of seaweeds per person per day (Cornish et al., 2015).

Algal foods are rich in vitamin C, vitamins thiamine (B1) and riboflavin (B2); vitamin A precursors, such as β -carotene, vitamin E and antioxidants (Sanz-Pintos et al., 2017; Wells et al., 2017) although amounts vary, depending on sample processing methods and environmental and seasonal factors.

There are opportunities to spread rapidly new technological and scientific knowledge on these items. Seaweed patents registered between 1980 and 2009 were dominated by applications of the food industry (37.7%) and were primarily owned by Asian countries. This reflects the growth and consumption of seaweed as traditional activities in these countries. Processing improves bioavailability, and seaweed has been successfully

incorporated as a functional ingredient into several foods (e.g. pasta, bread) (Bleakley & Hayes, 2017).

Due to the credibility that has emerged for algae cultivation, government agencies are able to support the development of it, particularly in rural communities, providing an opportunity for developing nations to grow (Rebours et al., 2014). There are clearly good opportunities to develop these cultivations further and to increase algal production, with more foodstuff in a variety of formats, as listed above.

There is also a potential to improve the sustainability of fish and shellfish aquaculture in integrated cultivation initiatives. Cultivated seaweed plots rapidly attract biodiversity, including a significantly larger number of fish species and individuals (Duarte et al., 2007). The research on seaweed to mitigate the environmental impact of intensive finfish aquaculture through integrated multi-trophic aquaculture is receiving increased attention in developed countries. Seaweed farming now expands across several continents from South-East Asia to South America, Northern Europe, Canada and East Africa, contributing to global food security, supporting rural livelihoods, alleviating poverty and improving the health of our oceans (Cottier-Cook et al., 2016).

Like terrestrial plants, macroalgae grow on sunlight, inorganic nutrients and water (trophic level 1). Unlike agriculture, however, mariculture of macroalgae does not require artificial fertilizers and irrigation. The occurrence and production of natural macroalgae in the ocean is strongly limited by available habitat, since they are attached to bottoms that are sufficiently shallow to provide sunlight for photosynthesis. In cultivation, however, macroalgae are attached to artificial substrate in the free water masses which, in theory, allows for large-scale cultivation everywhere in the uppermost meters of the ocean. Consequently, the biological production potential for providing large quantities of food and biomass from macroalgae mariculture is much larger than for any other group of marine organisms including microalgae, as these need infrastructure like enclosed lagoons and tanks, in addition to fertilizers and artificial light. However, despite the high current production volume (30 Mt per year) and high annual growth rate of macroalgae mariculture, there are several constraints for a full realisation of the potential.

Today's biological and technical constraints for harvesting more algae

- **Competition for space in coastal areas.** The correct siting of cultured seaweed farms will be vital to ensure sufficient light (considerable reductions in yield with increasing depth are observed) and nutrients, while minimising disruption to other activities and the environment. Construction and operation of land-based tanks is expensive, and involves the loss of terrestrial sites that could be used for other purposes (Milledge & Harvey, 2016).
- **Lack of offshore production techniques.** Offshore deep-sea environments pose significant engineering challenges and the design of structures that will allow seaweed to survive aggressive ocean conditions.
- **Insufficient seed quality.** Widespread clonal propagation techniques, or propagation from a limited pool of parent individuals, results in an increased

risk of disease and plants that need to be discarded later (Shan, Pang, Zhang, Yakovleva, & Skriptsova, 2011).

- **Maintenance of native genetic resources.** Existing and draft policies typically forbid or severely restrict the use of non-native genotypes in seaweed aquaculture because the practice contributes to the involuntary spread of alien species, resulting in costly containment and restoration measures.
- **Affinity for heavy metals.** Alginates (on brown algae, for example) bind metal ions very well and can gather toxic elements, including heavy metals (Zeraatkar, Ahmadzadeh, Talebi, Moheimani, & McHenry, 2016; Bleakley & Hayes, 2017; Wells et al., 2017).
- **Lack of low-cost, high-efficiency harvesting systems** that maintain the protein quality of the biomass and activity of compounds of interest to the food industry. Mechanical seaweed harvesting is costly, unselective, and prone to contaminate native stocks with cultured genotypes. For microalgae, harvesting and dewatering processes for concentrating dilute algal suspensions from lagoons or open ponds may account for 20–30% of the total production cost for microalgal biomass (Barros, Gonçalves, Simões, & Pires, 2015).
- **Seasonal variability affects nutritional content.** Protein levels negatively correlate with temperature and salinity (Marinho-Soriano, Fonseca, Carneiro, & Moreira, 2006) and also vary with location (Zhou, Robertson, Hamid, Ma, & Lu, 2015) and periods of nutrient limitation (Schiener, Black, Stanley, & Green, 2015), which have implications for food processing.
- **Food acceptability.** In Western cultures, algae are not a commonly-used ingredient for food. Therefore, microalgae constitute a very new and, in most cases, an unacceptable addition to foods. New food applications and products are needed.

3.2.4 Biological potential of mariculture of molluscs and other filter feeders

Numerous mollusc species are produced in the world. The Pacific cupped oyster (*Crassostrea gigas*), native to northeast Asia, has been introduced worldwide for the purpose of aquaculture and is among the most important cultured shellfish species in the world (FAO, 2017c). The history of oyster culture in Europe involves a succession of development phases with different species, followed by collapses caused by diseases. The indigenous species, *Ostrea edulis*, was replaced first with *Crassostrea angulata*, the Portuguese oyster, and then by *C. gigas*, the Pacific cupped oyster (Grizel & Héral, 1991). The flat oyster became a food resource already in the prehistoric period (Gutiérrez-Zugasti et al., 2011), but oysters and more generally molluscs still represent an important food resource in Europe, although small in comparison to the mollusc consumption in Asia.

Shellfish farming is mostly performed in an open environment. Most of the species consumed are bivalves which are sessile filter feeders, i.e. animals feeding on phytoplankton, other microorganisms and dead particulate organic matter. They are not fed formulated feeds and are therefore not limited by feed resources from their environment. The nutritional quality of shellfish is largely a reflection of the quality of

the environment in which they are grown. They therefore appear, for the consumer, as 'natural' products. They are characterised by a low lipid content, but a high concentration in selenium, potassium, iron, zinc and iodine, which are considered positive for human health. However, in contrast, as filter feeders, they can also carry or accumulate toxic algae, virus or bacteria, which can be 'naturally' detrimental to human health (ANSES, 2010).

Oyster fisheries have shown poor sustainability in many cases. Restoration of over-exploited wild stocks has often been of limited success due to continued exploitation, habitat degradation, or diseases. The culturing of oysters, on the other hand, provides longer-term productivity of nearshore marine and estuarine habitats. In Europe, oyster farming was only a gathering and fishing activity until the middle of the nineteenth century. Then, farmers grew seed collected from the wild, whereas nowadays, hatcheries of spat secure the availability of seed and allow the production of genetically-improved oysters, through polyploidy and selective breeding. The proportion of spat produced in hatcheries has increased considerably in recent decades, notably in countries where summer water temperatures are too low to allow reproduction (e.g. *C. gigas* on the west coast of North America). Both activities (recruitment in the field and hatchery production) appear complementary and have greatly improved to represent a great potential for mollusc production today.

Techniques in hatcheries and nurseries have developed in order to secure production, which can be limited by stocking density and disease. In the field, the high diversity of rearing areas has given rise to the development of several cultivation techniques (Nash, 1991). 'On-bottom cultivation' involves sowing of the oysters directly onto the intertidal seabed, or in deeper water, 5 to 10 m in depth. Off-bottom culture is done using plastic mesh bags deployed on trestles in the intertidal zone. Suspended culture is done by hanging oysters fixed on ropes, or in baskets from special frames in lagoons, or on lines in the open sea.

Mortality episodes may affect shellfish farming of adult or juvenile oysters and mussels. However, breeding programmes have developed all around the world to produce animals resistant/tolerant to several diseases, in order to sustain shellfish production. At the same time there is a wide consensus that mussel farming is one of the most sustainable mariculture practices and has therefore an important potential for further extension (Danovaro, Gambi, Luna, & Mirto, 2004).

Additionally, the production of triploid cupped oysters and the establishment of selective breeding programmes have enhanced the development of hatchery-produced spat. In Europe, the main commercial hatcheries are established in France, the Channel Islands, UK and Ireland (Lapègue, Boudry, & Gouilletquer, 2006). Polyploidy application to shellfish production could also be considered as a way to limit interactions with wild stocks, considering the sterility of triploids as, for example, in the United States. Some production methods have raised the issue of the food acceptability in some areas, especially in Europe, because oysters are considered to be a 'natural' food.

Like macroalgae, bivalves and other filter feeders (e.g. tunicates, generally classified as TL2 organisms) feed on nutrients (phytoplankton and other particulate organic material)

that are naturally occurring in the seawater. It is paramount that this group of animals extract their feed from the ocean so that culture stocks are not dependent on the provision of limiting feed resources (the way fish and crustaceans are). Furthermore, placing filtering organisms, which by nature are bottom-attached (2D-habitat), in the 3D water column with suitable currents, enables area-intensive production (i.e. high production per m²).

Thus, as with macroalgae, the biological potential for providing more seafood and biomass by cultivation of filter feeders is large. Many mollusc species have long traditions as seafood and are attractive for humans in most regions of the world. Test production of mussels in offshore locations has given positive results in the US and other countries (Lovatelli, Aguilar Manjarrez, & Soto, 2013). The technology for coastal farming appears simpler than for fish, suggesting that the potential for increasing mollusc production worldwide may be very high in the century to come.

Today's biological and technical constraints to realising the potential of mollusc farming include:

- Insufficient water quality in certain coastal areas;
- Competition for space in coastal areas;
- Insufficient technology/experience for open ocean farming;
- Episodes of increased mortality in shellfish farming appear to have accelerated. Breeding programmes have been established all around the world and efforts are being made here to produce animals that are resistant to diseases in order to sustain production;
- Concern for the negative effects of farming on wild shellfish populations.

3.2.5 Biological potential of fish mariculture

Fish have been cultured in freshwater for centuries (Duarte et al., 2007), and the production in seawater (i.e., sea- and brackish water, c.f. FAO) has increased steadily over time (Figure 7). The FAO database goes back to 1950 and lists 185 cultured marine fish species in 2015. Atlantic salmon exhibit the highest production (35% of total fish production), followed by milkfish (15%), rainbow trout (4%) and Japanese amberjack (3%). Then follows coho salmon, gilthead seabream and European seabass. Many fish species have a relatively complex production technology for their juvenile stages, and Japan (as a pioneer) and other developed countries have mostly led the way in establishing fish mariculture. Europe is currently a major region for farming of marine and anadromous fish (27% of total global production in 2015), to a value of 8.47 billion €.

Cage culture is the dominant technology for the on-growing of fish in the sea, but some production takes place in ponds and in land-based fish farms, with flow-through or with recycling of water. Cage mariculture has so far required relatively sheltered coastal locations (<4 m significant wave heights), but large systems for open ocean farming (9 m significant waves) of salmon and other species are now being tested (SalMar, n.d.). The FAO has, for a long time, requested systems for offshore mariculture because many

coastal states interested in undertaking mariculture have open coasts only (Lovatelli et al., 2013). Such systems are requested for fish, and also for shellfish and macroalgae.

Most fish species cultured in the sea are carnivores feeding on trophic levels 3 to 5 in nature. Due to comprehensive R&D activity undertaken by research institutions and leading feed companies, pelleted feeds which secure fully adequate nutrition, high production yields and low environmental footprints have been developed and are today used in all modern mariculture of fish. Because of the limitations in LC n-3 rich lipids for the feed, their contents in the feed has been reduced over time and marine resources constitute now around 18-21% of the dry feed. Plant resources from agriculture have replaced the marine resources (79-89%).

The high use of plant resources in this feed has reduced the TL of the farmed carnivores in mariculture. Figure 10 shows how the trophic level of farmed Atlantic salmon has developed over time, from the wild stage. The species is now produced at a TL of 2.43, around two TLs lower than the wild salmon (Froese & Pauly, 2017). This means that a kilo of farmed salmon requires only 1% of the limiting marine primary production resources compared to one kilo of wild salmon or another wild fish predator feeding on the same TL e.g., tuna. Today's feed production has brought cultured marine carnivores down in the food chain and is now close to the herbivore level. Farming of carnivores in mariculture has been criticised, due to a high fish-in to fish-out ratio, i.e. that much more fish has been used as feed than fish produced. This critique does not apply for mariculture using modern pelleted feed, but it still applies to production techniques where, for example, captured fish are thrown as feed ('trash fish') into the cages, e.g. in small-scale on-growing of captured wild fish, such as tuna.

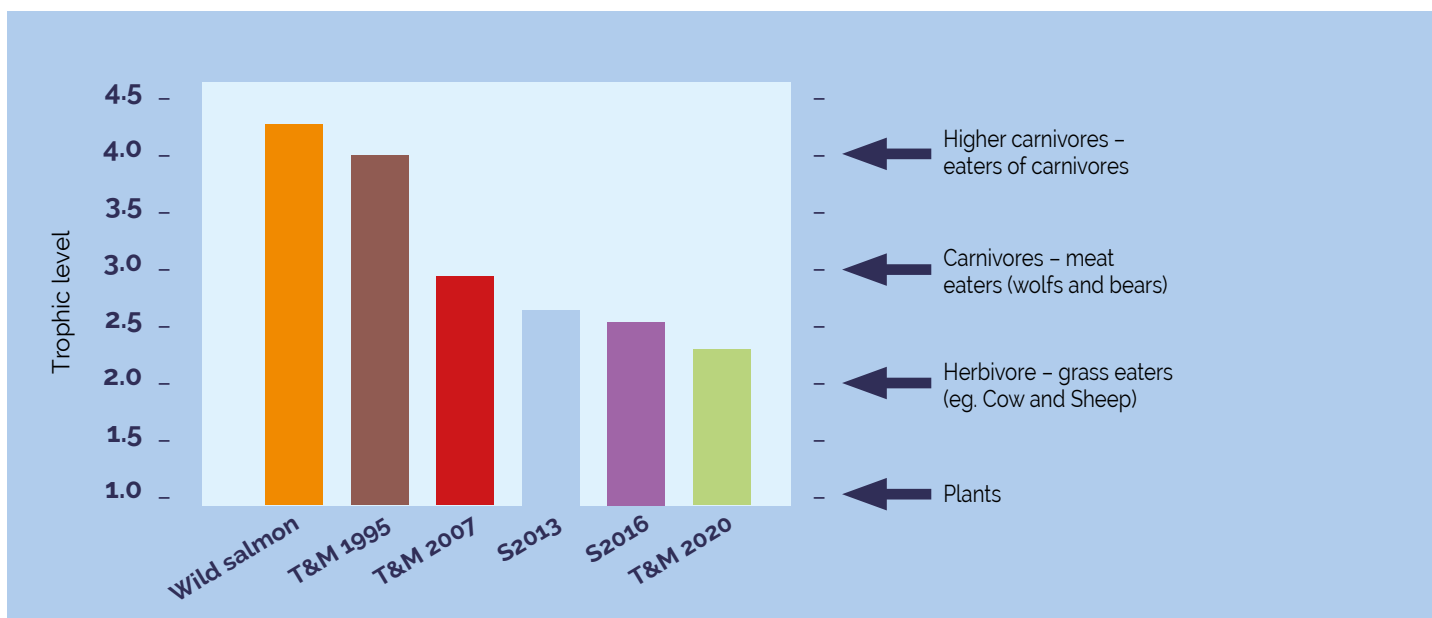


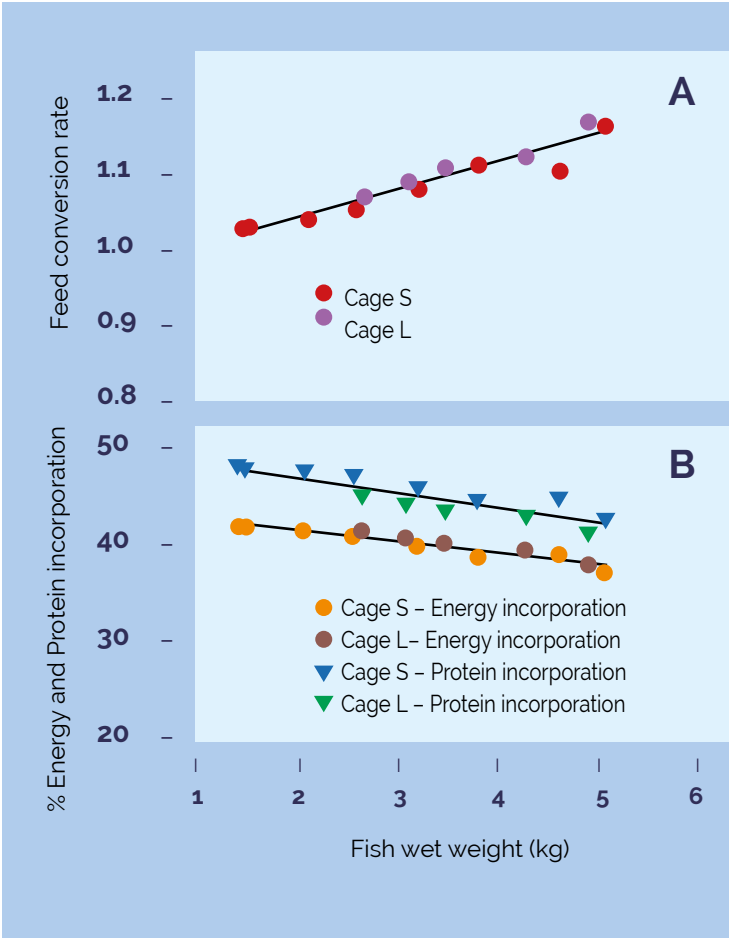
Figure 10. Trophic level of wild Atlantic salmon (Froese & Pauly, 2017) and farmed Atlantic salmon at different times, using the equation: $TL_i = 1 + j (F_j \times TL_j)$ where F_j is the fraction of a food organism, TL_j is its trophic level and j is the number of feed organisms (Gascuel & Pauly, 2009). Trophic level was calculated based on fractions of fishmeal and fish oil used in pelleted feed given by Tacon and Metian (2008) for 1995 and 2007 (T&M 1995, T&M 2007). TM2020 is a prediction for 2020 given by Tacon and Metian (2008). S2013 is based on values of fishmeal and fish oil used in pellet fish feed for marine fish in 2013 obtained from Skretting AS. MS2016 is representative for 2016 and is taken from Marine Harvest (2017). Arrows and trophic levels of agricultural stocks are included.

In addition to a low TL, the conversion efficiency of the feed in mariculture is higher than in natural food chains in the sea (10%; Ryther, 1969; Pauly & Christensen, 1995). Figure 11 illustrates feed utilisation efficiencies measured in two large salmon cages in normal commercial production (Wang et al., 2013). The mean food conversion rate is 1.09 kg dry feed used per kg wet fish produced (range 1.03-1.16) (Figure 11A), typical for commercial salmon production. The amount of 1.09 kilo of dry feed contains 0.23 kg of marine resources (21%, representative for Atlantic salmon produced in Norway), needed for the production of one kilo wet weight fish. This means that <1.2 kg of forage fish is needed for producing one kilo of salmon, suggesting that mariculture of fish represents an upgrading of marine fish resources. The situation is similar for other fish species. It also implies that direct human consumption of a kilo of forage fishes used to produce fishmeal and oil (see Section 3.1.5) reduces the mariculture potential by one kilo, i.e. the same amount. Moreover, the fraction of marine ingredients in fish feed is still decreasing (Figure 10).

Figure 11. Production efficiency of farmed Atlantic salmon in two full-scale cages (Cage S and Cage L) with the capacity of holding up to 1000 tonnes of fish (March to October).

A: Feed conversion rate (kg dry feed (kg wet fish produced)⁻¹) as a function of fish weight

B: Energy and protein incorporation efficiency as a function of fish weight. Carbon is used as a proxy for energy and nitrogen for proteins. Data from Wang et al. (2013). Values of food conversion rates slightly above 1 are representative for Norwegian salmon farming.



The food conversion rate reflects the efficiency of carbon (or energy) and nitrogen (protein) use in salmon farming (Figure 11B). As much as 36-40% of the feed energy is incorporated in fish flesh and 42-48% of the protein, which are much higher than for wild fish stocks (10%). Fish are cold-blooded and have an almost neutral weight in their environment. This reduces the energy needs for maintenance compared to that of terrestrial warm-blooded animals, and such high production yields cannot be obtained for agricultural livestock (de Verdal et al., 2017).

3.2.6 Potential sources of LC n-3 rich lipids needed in fish feed

The future potential of fish (and shrimp) mariculture depends on the availability of suitable new feed resources rich in LC n-3 fatty acids (Duarte et al., 2009; Olsen, 2011). As noted above, the content of these fatty acids in the feed has been brought down over time but there is a limitation as to how far down these essential nutrient components can be reduced, without affecting fish health and welfare.

There are optional new harvested resources among wastes from fisheries and among non-utilised marine animal resources (see Table 3). Other options are cultured resources, such as macroalgae, or single cell biomass of thraustochytrids/microalgae of appropriate quality, and oils from transgenic higher plants. Wastes from agriculture, together with methane, can act as substrates for microorganisms.

Resource	Status
Harvested resources	
Discards and offals in fisheries	FAO reports global fish losses (including discards) and waste amount to 35 % of landings, which correspond to 29 Mt of a marine landing of 82 Mt in 2015 (see Section 3.1). Lack of appropriate fishing gear, low capacity to store wastes on vessels and to process and deliver discards, and lack of management systems aiming to reduce discarded bycatches are among the main constraints for using these wastes.
Mesopelagic fish and other marine animal products	The potentials of using mesopelagic fish as feed resources are very big (stocks of 100-1000 Mt), but there are major concerns on species biology, biodiversity of stocks, sustainable fishing strategies, and fishing technology that will be efficient and have acceptable energy and environmental costs (see Section 3.1). The resources are accordingly not easily available.
Harvested zooplankton (red feed/Antarctic krill)	Sustainable harvesting of Antarctic krill of up to 8.6 Mt per year is suggested, constituting some 10% of the annual global catches. There are, however, strong ecological concerns. The costs of harvesting is also still relatively high, and it will constrain harvesting at a cost that are acceptable for feed ingredients (see Section 3.1)
Cultured resources	
Wastes from agriculture	Waste products from agriculture contain no LC n-3 fatty acids, but may have other valuable ingredients and short chain n-3 fatty acids. Wastes, together with methane, may be used as substrates for growing single cell biomass (see below).

Resource	Status
Single-cell biomass with LC-n-3 rich lipids (microalgae/thraustochytrids) produced by methods of industrial biotechnology	Production of GMO yeast (Xue et al., 2013) and thraustochytrids/microalgae are being commercialised, using methods of modern industrial biotechnology. Reported productivities for the human nutraceutical market suggest profit down to 15-20 €/ kg of EPA/DHA. Thraustochytrids have high DHA levels (reviewed by Aasen et al., 2016) and producers are already linked to aquaculture feed companies. Production of LC n-3 rich microalgae has also major attention (e.g. Mühlroth et al., 2013; Chauton, Reitan, Norsker, Tveterås, & Kleivdal, 2015).
Farmed seaweed	Farmed macroalgae are apparently an attractive source of feed ingredients, but their lipids do not have the right quality, as the fraction of 20:4 n-6 (arachidonic acid) is very high (see above). Proteins and other feed ingredients from macroalgae can become important, because macroalgae on TL 1 can be produced in very high quantities (see macroalgae section above).
GMO-higher plants, with LC-n-3 rich lipids	Efforts through more than 15 years to transfer LC-n-3 fatty acids genes to higher plants appear at last to be successful, great progress has at least been made. Both EPA and DHA can be produced in engineered <i>C. sativa</i> seeds in fractions up to 17- and 4 mol% of total fatty acids, respectively (Napier, Usher, Haslam, Ruiz-Lopez & Sayanova, 2015; reviewed by Usher et al., 2017). The <i>C. sativa</i> plants are transgenic, but not the oils. The further application of such oils for fish and shrimp feed is not legally straightforward, but such oils may become globally available relatively fast.

Table 3. Optional new feed resources with LC n-3 rich lipids for fish feed.

There are two main avenues for increasing feed resources for fish and shrimp farming:

- 1 If discards from fisheries, along with new harvested resources (such as mesopelagic fish, krill and large copepods) become available over time, (Table 3 and Section 3.1), this can provide the basis for a new production of one kilo fish (shrimp) per kilo of new captured feed resource (wet weight). Mariculture will then, regrettably, still depend on and be constrained by captured marine-fed resources.
- 2 If the new LC n-3 rich feed resources are cultured instead (single cell biomass of thraustochytrids/microalgae, cultured seaweed, LC-n-3 rich oils from transgenic *Camelina sativa*, or other cultured animals), there will be no direct link and constraint on mariculture by resources from capture fisheries. Mariculture production of fish and shrimps will not be linked to, or constrained by, resources from fisheries, but perhaps still partly depend on cultured *Camelina sativa*. De-linking mariculture from fisheries will, over a long-term perspective, allow an animal seafood production of the same magnitude as that of agriculture.

With new LC n-3 lipid resources for fish and crustacean mariculture available, and an expansion of macroalgae and mollusc mariculture, global mariculture may grow to

levels more comparable to agriculture. A long-term objective for future mariculture should also be that new feed resources are taken preferably from outside the human food chain. A self-sustaining food chain for mariculture, based on mainly cultured resources, should be the ultimate objective (Lovatelli et al., 2013), but this cannot be achieved in a short amount of time. Until that time, feed resources will remain a mixture of cultured and harvested resources.

Today's biological and technical constraints for increased fish mariculture are:

- Availability of new suitable feed resources rich in LC n-3 fatty acids;
- Competition for space in certain coastal areas;
- Technologies for farming in open and exposed water are lacking, but in progress;
- Environmental concerns related to the release of organic material and pharmaceutical products. Poorly-regulated mariculture, using trash fish feed, may have strong environmental footprints in locations with poor water renewal;
- Concern for interaction with wild stocks, both genetically and the risk of disease spreading (e.g. parasites);
- The perception of fish mariculture is often negative, which might cause a lack of governmental support for development.

3.2.7 Biological potential of crustacean mariculture

FAO statistics (FAO, 2017c) reveal that 57 species of crustaceans are cultured in marine and brackish waters worldwide. Shrimps are by far the dominating group, and a few species constitute the majority of the production. Total crustacean production in 2015 was 4.88, with a production of 3.67 Mt of whiteleg shrimp (*Peneaus vannamei*) and 0.63 Mt of giant tiger prawn (*Penaeus monodon*) (Figure 12). One crab species, the Indo-Pacific swamp crab, is produced in quantities of 0.12 Mt. The whiteleg shrimp is an omnivore species, with lower LC n-3 requirements than most cultured fish species, but increased production nevertheless depends on new sources of LC n-3.

Shrimp production is normally undertaken in pond culture in tropical waters. The production volume has more than doubled over the past ten years, and the value has grown even more, as shrimps are highly-valued seafood. As of 2014, the major shrimp-producing countries are China, followed by Thailand, Indonesia, India and Vietnam in Asia, and Ecuador, Brazil and Mexico in Latin America.

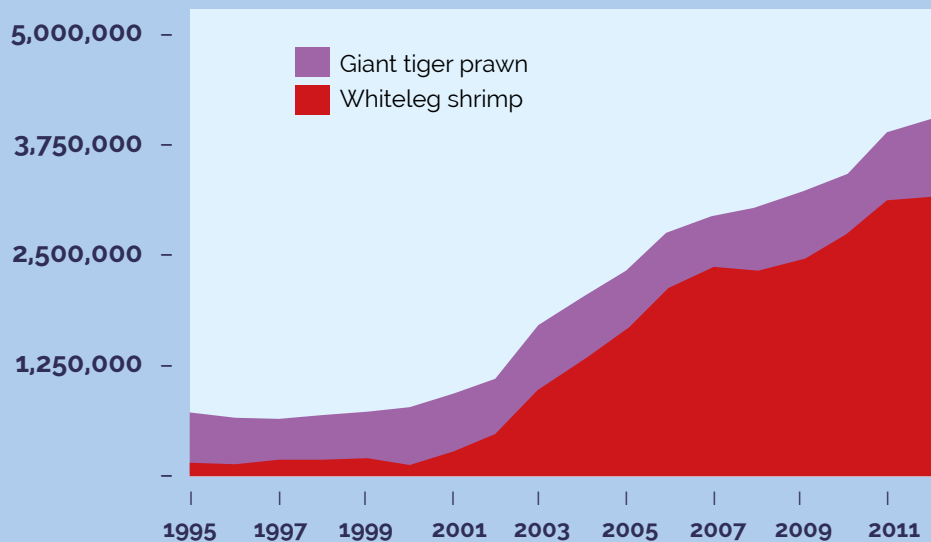


Figure 12. World penaeid shrimp production over the past 15 years (in tonnes) *Penaeus vannamei* production has vastly outdistanced *P. monodon* in the last 10 years. This is mainly due to availability of domesticated and selected broodstock of *P. vannamei*, lower growth rates and lower capacity of *P. monodon* to grow in high densities.

Since 2012, diseases in intensive *P. vannamei* production (virulent vibriosis in combination with different viruses and microsporidia) have had a devastating impact, with Asia particularly hard hit. The Americas have also been affected, but the volumes there are much lower. Although there is some recovery, this is slow, with the disease issue rampant almost everywhere.

Today's biological and technical constraints for crustacean mariculture include:

- Insufficient focus on selective breeding programmes;
- Competition for space in coastal areas;
- Crustacean farming is dependent on formulated feeds and adequate feed resources, similar to fish;
- Diseases (with a focus on prevention) and environmental impact are two main challenges in the cultivation of crustaceans, particularly shrimp.

3.2.8 Integrated multi-trophic mariculture (IMTA)

In Asia, it is a very old tradition to integrate the production of species from different groups in freshwater aquaculture. Integration of seaweed and mollusc farming was started in the late 1950s in coastal areas of China, and later extended further with fish and crustacean species (Dong Shuanglin, pers. comm.). Integration in mariculture has become more common in the Western world in the 21st century (Chopin et al., 2001). The 'win-win' in this so-called multi-trophic aquaculture situation is that added-value to feed investment may be obtained, whilst simultaneously removing waste from the system. In this way, the pressure on the benthic and pelagic ecosystems are reduced and environmental influences mitigated. There are two main modes of integrating aquaculture:

- 1 Wastes dispersed from fish fed in cage systems/land-based farms can be used as a resource for other organisms with a different feeding behaviour/

trophic level. Inorganic nutrients, for example, released by excretion from fish, are nutrient resources for macroalgae, and particulate wastes from fish are feed resources for species of filter-feeding shellfish or for a bottom-living waste-consuming invertebrate (e.g., Wang et al., 2012).

- 2 Culture of selected species could be based on, or partly on, wastes taken from fish. Marine wastes can also be used for agricultural species (aquaponics).

The potential of IMTA is that higher resource efficiency can be obtained, while also reducing the marine footprint from feeding mariculture. The increased production will always be related to the input of feed and therefore also by the constraints of feed resources of fish mariculture, if fish culture is the driver of the IMTA. There are, however, reports from the integration of cultures in Asian countries, where the health of the cultured organisms are better when grown together with other organisms, than in monoculture. Examples are intensive shrimp farming integrated with marine tilapia and *Caulerpa* seaweed species in coastal ponds in Thailand (Robins McIntosh, pers. comm.), different species of shrimp, seaweed, jellyfish and sea cucumber in coastal ponds in China (Dong Shuanglin, pers. comm.). Public acceptance of such mariculture has been better if the fish are grown together with macroalgae. In this way, IMTA has a higher public acceptance.

IMTA types of mariculture are most common in Asian countries. Figure 13 illustrates how macroalgae, shellfish, sea urchins and sea cucumbers are grown together in Sanggou Bay in eastern China. The farmed macroalgae are used for different purposes, for example, as feed for humans and abalone farming, and for further processing in bio-refineries where the main components of the algae are extracted, concentrated, and later used for many different industrial purposes.

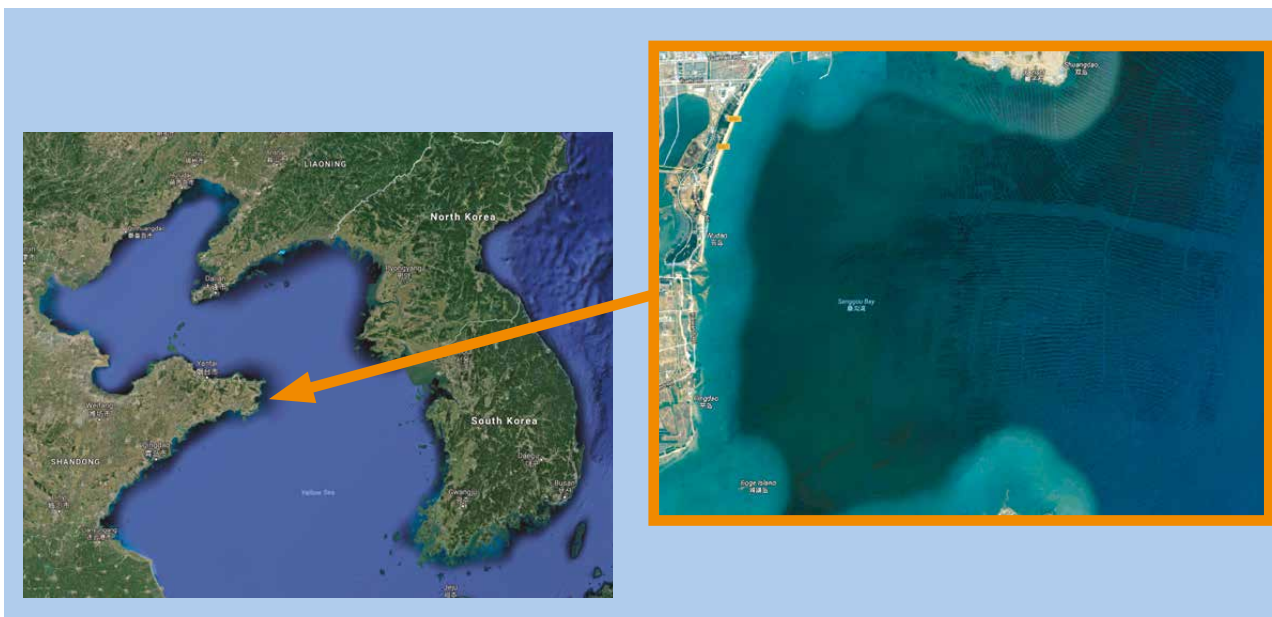


Figure 13. Large-scale integrated multi-trophic aquaculture in Sanggou Bay, east of Qingdao in the Shandong province of China. The aquaculture structures are visible in Google Maps (Imagery ©2017 TerraMetrics). The macroalgae *Saccarina japonica* are the main product but a high number of fish and shellfish, as well as bottom-living invertebrates, are cultured.

The costs of developing aquaculture systems for IMTA in Western countries can be high, and there can be severe risks and limited incomes from the beginning. Initiatives have been taken to establish the integration of industries on a higher level of innovation, for example, the classic OTEC (Ocean Thermal Energy Conversion) process from the 1970-80s, which is well-known (Makai Ocean Engineering, n.d.). On the main island in Hawaii, one major OTEC project delivers seawater to several aquaculture farms. There are now other and more recent initiatives to combine IMTA and energy production in offshore wind parks in the North Sea. The idea is that the aquaculture systems get options for anchoring and lower costs of operation, whilst the income of mariculture might create important added-value, along with the energy production.

Constraints for realising the IMTA potential include that:

- Fish producers in the Western world will normally not accept the risks of having integrated aquaculture systems close to their fish cages (e.g., rope cultures with macroalgae or shellfish). This is because of an increased probability of harmful interactions, escapes and losses of fish during bad weather. The value is normally higher for fish than for the other integrated organisms.
- There are increased risks involved while the technology for IMTA remains immature.
- The most severe constraint of IMTA is likely that the added-value obtained through better use of feed resources is relatively low at present. Government incentives are being considered to promote this type of more eco-friendly aquaculture.

3.3 UNCERTAINTIES ASSOCIATED WITH CLIMATE CHANGE AND POLLUTANTS

Background

This chapter addresses questions around impact of climate change and pollutants, both globally and regionally. Changes in fishing practice, such as waste reduction or changes in fishing gear, are discussed in Section 3.1.2.

Climate change alters the physical, chemical and biological properties of the ocean (Pörtner et al., 2014). The current rise in anthropogenic CO₂ directly changes the chemistry of the ocean, a phenomenon termed 'ocean acidification', and indirectly results in warming, increased stratification of the upper water column and oxygen loss.

Climate change and extreme events are expected to have a range of effects on marine ecosystems, their function and biodiversity and therefore impact on the ability of the marine system to provide food. Emission pathways over the next decades and century are still uncertain; how marine ecosystems (e.g. in terms of food web structure and biogeochemical cycles) respond is even more unpredictable (Gattuso, Hoegh-Guldberg, & Pörtner, 2014). Ecosystem impacts may be driven by warming, changes in circulation and/or habitat, through altered pathways within biogeochemical cycles and food webs. These result in loss of habitat, the movement of species, and the spread and increase of disease and invading novel species. Environmental changes

can impact positively and negatively on farm profitability, depending on target species and farm location.

To date, climate change-driven trends in multiple ecosystem drivers are within the range of natural variability. They are predicted to emerge from the background of natural variability in 55% of the ocean within the next 15 years and propagate rapidly to encompass 86% of the ocean by 2050, under a 'business-as-usual' scenario (Henson et al., 2017).

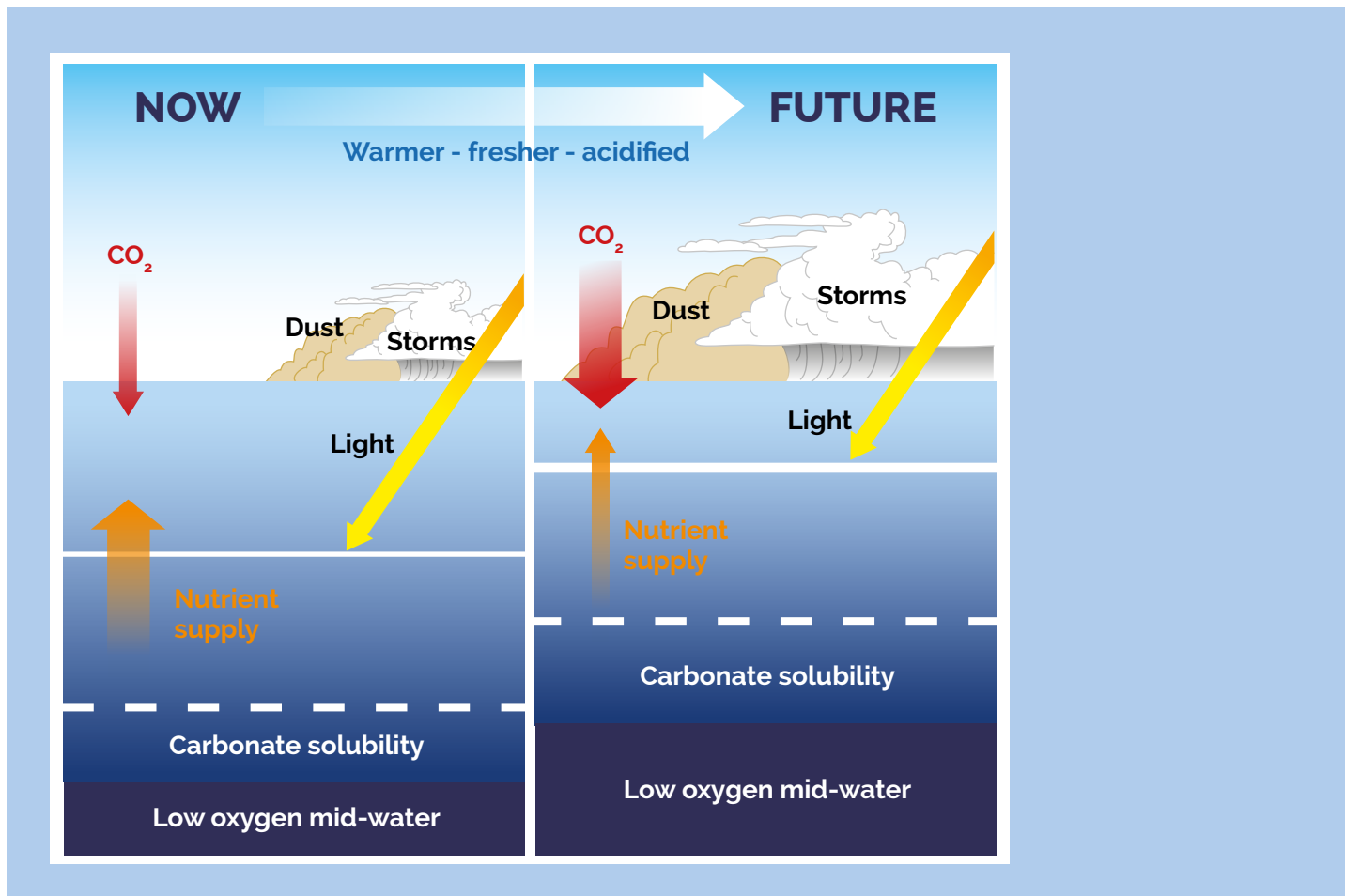


Figure 14 (Reusch & Boyd, 2013). Projected alteration (magnitude and frequency) of oceanic fluxes and atmospheric events, due to a changing climate in the coming decades. Ocean properties will be altered, from the sunlit surface layer to the mid-water stratum. In the surface ocean, the depth of the mixed layer (solid horizontal line) will shallow, resulting in higher mean light levels. Increased density stratification (i.e., a strengthening sea water density gradient represented by the increasing thickness of the solid horizontal line) will reduce the vertical supply of nutrients for photosynthesising organisms residing in the mixed layer. Anthropogenic CO₂ will acidify, that is, lower the pH of the surface ocean (note this happens in a pH range higher than 7, such that oceans will remain alkaline but less so, due to acidification). The penetration of acidified waters to depth will result in a shallower depth (dashed horizontal line) at which CaCO₃ structures, such as shells, dissolve. At depth, the location of low-O₂ waters will progressively become shallower. In addition, changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean biota and hence ecosystems (Pörtner et al., 2014).

3.3.1 Climate change affects species vital for food production

Warming can be expressed in the marine habitat via changes in mean annual temperature, seasonal differences and changes in frequency of severe weather events. Regionally, the largest global warming is expected in northern high latitudes (Rhein et al., 2013). Intense warming of sea surface temperature over the last two decades has been documented in semi-enclosed European and East Asian Seas (Belkin, 2009). Locally, changes in the flow of western boundary currents can lead to hotspots, i.e. areas which are warming significantly faster than the global average (Hobday, 2014).

Warming impacts the pelagic ecosystem, both directly and indirectly:

- Decreased supply of nutrients, due to higher stratification of the surface ocean, leading to an increase in the extend of oligotrophic gyres (Cabr e, Marinov, & Leung, 2015);
- Impacts on the hydrological cycle, changing runoff from the hinterland into the ocean;
- Increasing light availability for photosynthetic organisms living in the upper part of the ocean;
- Storminess; and
- Through the effect of increasing temperatures on the rates of biological processes.

Consequently, temperature affects the development, body size and abundance of the catch species, geographic distribution of both primary producers and consumers, timing of phenology of interdependent species and, ultimately, community structure (see P rtner et al., 2014 for a recent overview) and has the potential to lead to local and global extinctions. Species with narrow temperature ranges and those living close to upper thermal limits are the most vulnerable (P rtner et al., 2014). Which of these factors will dominate in a region and at a given time depends on the hydrographic conditions, the composition of the pelagic community and the activities of its components (Riebesell, K rtzinger, & Oschlies, 2009). The resulting changes in trophic interactions affect fisheries across the world (Cheung, Watson & Pauly, 2013; see 3.3.2. and 3.3.3).

Oxygen concentrations are highly sensitive to changes in ocean physics and biology and are projected to decrease, due to climate change (Oschlies, Schulz, Riebesell, & Schmittner, 2008). In coastal systems, oxygen loss may also result from cultural eutrophication (Diaz & Rosenberg, 2008; Middelburg & Levin, 2009) and can be associated with high nutrient loss from aquaculture (Grossowicz, Tchernov, & Gildor, 2017).

An expansion of oxygen minimum zones is projected to reduce the habitat for tropical pelagic fishes (Stramma et al., 2012). In the eastern tropical North Atlantic, the oxygen minimum zone (OMZ) is currently around 300 to 600 meters depth (Hausse et al., 2016) in the habitat depth of mesopelagic fish (see Section 3.1.3). Hypoxia can lead to changes in behaviour, distribution, functioning and, at very low oxygen levels, to mortality of organisms. A study across the continental shelf of the west coast of North

America showed a clear relationship between catch per unit effort and oxygen levels in 19 out of 34 groundfish species, specifically flatfishes, roundfishes and thornyheads, with negative impacts on another 7 species (Keller et al., 2017), while rockfish catch was not impacted by oxygen levels.

In the open ocean, the habitat of the blue marlin, for example, is bounded by low oxygen conditions, impacting migratory behaviour (Carlisle et al., 2017). The response of marine organisms to this low oxygen zone is variable; avoidance (most calanoid copepods), partial living in the OMZ (ostracods, polychaetes and krill species) or migration through the OMZ can occur. The compression of habitat increases prey-predator encounter rates and creates foraging hotspots for higher trophic levels (Hauss et al., 2016).

The interaction of drivers (of changes in the ocean) can enhance, reduce or even reverse impacts and are often difficult to predict without mechanistic understanding of the underlying drivers (Kroeker, Kordas, & Harley, 2017). At high temperatures, oxygen supply can become limited, impacting key functions (Pörtner & Farrell, 2008). In turn, high oxygen alleviates thermal stress in fish and molluscs (Pörtner, 2006). Experiments combining warming and the resulting increased metabolic demands, with low oxygen, highlight the additive effect on krill species and show potential implications for the food web (Tremblay & Abele, 2016). Similarly, the combined warming and expanding hypoxia may cause the decline of stocks of mesopelagic and demersal fish in the California current system (Koslow, Goericke, Lara-Lopez, & Watson, 2011). A meta-analysis of benthic fauna shows reduced survival by one third at 4°C warming, which is expected by the end of the century, due to lethal oxygen concentrations (Vaquer-Sunyer & Duarte, 2011).

Species responses to climate change are highly variable, with high levels of dispersal, non-specificity in food selection and geographic range all facilitating range extension (Sunday et al., 2015). Changes in species distribution in space and depth result in new ecosystem compositions, exclusion of some species and changes in food webs, but upscaling from individual species to ecosystems is a current gap in the scientific knowledge.

3.3.2 Climate change impacts on ocean harvest and management implications

Increasing temperatures and enhanced stratification are projected to affect biomass and the production of phytoplankton, with strong differences regionally. A reduction in net primary productivity is a combination of reduced supply of nutrients, due to stratification and changes in circulation, while increases are caused by lower light limitation and/or temperature limitation and increased nutrient supply (in upwelling regions under a shoaling nutricline) (Steinacher et al., 2010). Heterotrophic processes, such as feeding and respiration, are more temperature-sensitive than autotrophic processes such as photosynthesis (Rivkin & Legendre, 2001). At high temperatures, the concomitant increase in respiration and resulting reduction in growth efficiency results in a cap on productivity (Rivkin & Legendre, 2001). Globally, the best estimates

currently suggest a $6 \pm 3\%$ decline in global marine primary production by 2100 (Kwiatkowski et al., 2017).

Predicting fish communities in light of climate change and fisheries management need to be based on life history of the species and the trade-offs between growth, survival and reproduction (Pecuchet et al., 2017).

Changes at the base of the food chain can already be detected, with pronounced changes in zooplankton composition during the 20th century in the North Atlantic (Beaugrand, Luczak, & Edwards, 2009), the Japan sea (Tian, Kidokoro, & Watanabe, 2006), or the California current (Field, Francis, & Aydin, 2006).

Large reductions in net primary productivity (NPP) are expected in the tropics [$11 \pm 6\%$ according to Kwiatkowski et al. (2017); up to 30% according to Bopp et al. (2013),] and the North Atlantic [$\sim 50\%$, according to Bopp et al. (2013)], based on Earth System model projections under Representative Concentration Pathway RCP8.5 for greenhouse gas concentration trajectories by 2100. There is agreement amongst the models that NPP will increase in the western North Pacific, the Arctic Ocean, and in parts of the Southern Ocean (Bopp et al., 2013). Globally, a change in biomass at the lower trophic level by 15% is projected by 2100, and between 15 and 25% at higher tropic level, with migratory species less impacted than epi- and mesoplanktics (Lefort et al., 2015).

Fundamental ecosystem changes in response to natural climate variability in the 1920 and 1930s resulted in boreal fish such as cod, haddock and herring expanding their habitat northwards, changes in phenology, i.e. earlier arrivals and later departures, and in spawning sites (Drinkwater, 2006). Similar regime shifts are predicted for the future (Pörtner et al., 2014).

Changes in fish distribution impact commercial fishery catches, with resulting effects on profits (Cheung, Pinnegar, Merino, Jones, & Barange, 2012). 70% of the most abundantly fished species in the waters around the UK and Ireland respond to warming by changing distribution and abundance (Simpson et al., 2011). Smaller, warm-water species increased, while larger cold-water species decreased in abundance, resulting in higher catches of red mullet (*Mullus barbatus*) around the UK (Cheung et al., 2012).

Heavily-fished ecosystems are less resilient to climate change, compared with unexploited ecosystem states (MacNeil et al., 2010). Modelling studies based on the current temperature optimum of fished species, weighted by their annual catch (mean temperature of the catch, MTC), showed changes in 52 large marine ecosystems in response to warming (Cheung et al., 2013). A decrease in potential catches by more than 3 Mt per °C degree warming is projected for the coming century. The degree of warming is fundamental to the scale of the impact, with species turnover more than halved when warming will be below 1.5°C above the preindustrial level, compared to 3.5°C, (Cheung, Reygondeau, & Frölicher, 2016). The largest impacts are projected for the Indo-Pacific and Arctic regions.

Increased understanding of biology, ecology and stock dynamics is the basis of and foundation for management, to prevent further collapses and improve projections of recovery (Dickey-Collas et al., 2010). For example, spatial distributions of mackerel larvae suggest that the central North Sea is no longer an important spawning ground (Jansen et al., 2012). Changes in spawning requires constant management attention to prevent a recurrence of recruitment overfishing (Simmonds, 2007). Despite a large adult population, historically-low exploitation and Marine Stewardship Council accreditation, recruitment of herring larvae in the North Sea has been poor in the early 2000s, interpreted as a response to changes in plankton, resulting from warming (Payne et al., 2009). Management aimed at maximum sustainable yield fishing mortality targets needs information on inter-annual variation in total allowable catch (Dickey-Collas et al., 2010). Because the effects of climate change superimpose with those and with fishing, both components need to be examined in their potential interactions.

Studies clearly show that no single management lever is sufficient to address the wide range of climate change impacts and their consequences, and hence the mix of measures will need to change between systems and will need to be adapted through time (Fulton et al., 2011).

3.3.3 Regional differences in impacts on fisheries and dependencies

The impacts of climate change and its consequences across the food web differ regionally. Along the Atlantic Margin and North Sea, warming induces increased stratification, causes primary production and zooplankton biomass to decrease, whilst in the Barents, Baltic and Black Seas, primary production and zooplankton biomass increase (Chust et al., 2014).

Small body-size organisms are suggested to have sufficient food to meet their metabolic needs and additionally are exposed to a lower predation pressure, due to the decline of large predators. Projections suggest that biomass and maximum body-size will increase in the Arctic, due to loss of sea ice and warming by up to 30% at lower trophic level and up to 50% at higher tropic levels (Lefort et al., 2015). Other models have predicted 30–70% average increases in potential fish production at high latitudes and decreases of up to 40% in the tropics, based primarily on the effects of warming on species distributional ranges (Cheung et al., 2010).

Due to the increase in primary productivity, increases in catch potential by 2055 are projected for Norway, Greenland, Alaska and Russia. The eastwards shift in skipjack tuna in the Pacific, away from PNG and the Solomon Islands (which do not depend economically on the income), in response to future climate change, and towards French Polynesia and the Cook Islands, will increase revenue from fishing in these islands over the second half of the century (Bell et al., 2013). Increases in biomass relative to virgin stock levels there are expected to be in the order of 15% by 2035, rising to 40% by 2100 (Bell et al., 2013).

Models suggest that Denmark, Ireland and Latvia may be exposed to the greatest marine sector impacts, but overall dependence on fisheries is relatively low and

adaptive capacity is very high (Blanchard et al., 2017). However, the largest negative impact on people will occur where the dependence on marine resources is greatest, such as south-east Asia and western Africa, and are therefore of critical consideration in the context of food security (Hobday, 2014). Many low-income food-deficit countries and communities in developing countries depend on near-shore fisheries (Blasiak et al., 2017). At low- and mid-latitude, both lower and higher trophic level biomass and maximum body-size strongly decrease (Lefort et al., 2015), as declining food does not support the higher energetic demands, due to warming. The biggest potential catch losses are predicted to include Indonesia, the United States (excluding Alaska and Hawaii), Chile and China (Cheung et al., 2010). Many highly-impacted regions, particularly those in the tropics, are socio-economically vulnerable to these changes.

Barange et al. (2014) developed a model to link physical, biological and human responses to climate change in 67 marine-exclusive economic zones, which yielded around 60% of the global fish catch. Amongst the nations most dependent on food from the ocean, high catch is predicted along the west coast of Africa, (from Senegal to Nigeria), whilst the largest losses are predicted in South and Southeast Asia and Southwest Africa (from Nigeria to Namibia) (Barange et al., 2014). Declines in coral reef fish production in the Pacific Island countries will widen the gap of fish sustainability harvested from reefs and the amount needed to ascertain food security (Bell et al., 2013). In Papua New Guinea, Samoa, the Solomon Islands and Vanuatu, coastal fisheries will not supply the 35kg recommended for nutrient intake per person and year in the next decades (Bell et al., 2013). South Asia stands out as an area with decreasing catches, a high dependency on fisheries and a rapidly-growing population. The loss of wild catches in this area could be compensated by their rapidly-growing mariculture, however (Barange et al., 2014).

These changes suggest the opening of new fishing opportunities, depending on the interactions between climate impacts, fishing grounds and fleet types (Cheung et al., 2012). The changes will affect fishing regulations, the price of fish products and operating costs which, in turn, will affect the economic performance (Cheung et al., 2012).

3.3.4 Climate change impacts on mariculture harvest

Aquaculture contributes to global food security, nutrition and livelihoods (Blanchard et al., 2017). Seaweeds and molluscs constitute the largest proportion of mariculture production worldwide (De Silva & Soto, 2009). The dominant molluscs in aquaculture are oysters, mussels and clams. The main aquaculture activity in temperate regions is the mariculture of salmonids in cages (Halwart, Soto, & Arthur, 2007). Most mariculture species are sensitive to changes in climate patterns and extremes, particularly temperature and ocean acidification (Porter et al., 2014), but this warming and acidification is not geographically homogeneous. Summer heat waves have impacted bivalve production sites in the Mediterranean with effects on seeds, adult mortality and byssus attachment (Rodrigues et al., 2015). Of particular concern, especially for clams and other bottom-contact species, are the episodic anoxic events and de-

oxygenation of coastal waters, such as those observed in the Adriatic Sea (Danovaro, Fonda Umani, & Pusceddu, 2009).

In high latitudes, the growing season will increase, thereby potentially increasing the harvest. *Salmo salar*, on the other hand, has a relatively narrow temperature optimum and warming over 17 °C water temperature is considered detrimental (De Silva & Soto, 2009). The issue of escaped salmon from cages interbreeding with wild populations could be addressed with growing sterile fish, generated by gene alterations using the novel methods of CRISPR-CAS9 (Wargelius et al., 2016), if the consumer would be willing to buy the product.

Adaptive responses are selective breeding of tolerant strains (De Silva & Soto, 2009), as demonstrated for the Pacific rock oyster (Parker et al., 2012). *Crassostrea gigas* larvae have benefited from warming, by expanding the oyster's distribution to the north since the introduction of the species in Europe. It demonstrates the capacity of Northern European sites to produce mature oysters and consequently, a catch that can compete with Southern European sites. However, particularly in Northern Europe (Germany, Denmark), this capture is not considered as an opportunity, since this species is considered invasive.

While warming has been studied over decades, the biological consequences of ocean acidification in mariculture species are less well understood. The decrease of seawater pH has potential impacts on functioning, productivity, growth and survival of marine organisms (Kroeker et al., 2013). Shellfish are particularly vulnerable to declining pH and therefore the global production of shellfish is predicted to decrease in response to ocean acidification (Cooley & Doney, 2009).

Many, but not all animals, are often negatively impacted. Of the species-sustaining fisheries, corals, molluscs and echinoderms are considered more sensitive than crustaceans and fish (Pörtner et al., 2014). Species that can sustain calcification (given sufficient food), include important habitat formers like deep-water corals (Wall, Ragazzola, Foster, Form, & Schmidt, 2015) and economically-important species such as the blue mussel (Thomsen & Melzner, 2010). It is important to note that our present knowledge of pH/CO₂ sensitivities of marine organisms is based almost entirely on short-term perturbation experiments, which neglect the possibility of adaptation and with the potential to reduce the impact.

Low pH water flowing onto the continental shelf in response to ocean acidification causes problems for the shellfish aquaculture industry (Barton, Hales, Waldbusser, Langdon, & Feely, 2012). Seasonal upwelling of acidified waters onto the continental shelf in the California Current region has recently affected oyster hatcheries along the coast of Washington and Oregon (Barton et al., 2012), resulting in unprecedented levels of larval mortality (Barton et al., 2015). Local monitoring of the carbonate chemistry by the producers, in combination with researchers and engagement of policymakers, decreased the vulnerability in areas which otherwise would be more severely affected (Barton et al., 2015).

The exposure of the local producers to ocean acidification is a combination of ecological and social vulnerability. Ekstrom et al. (2015) found that 16 of the 23 regions around the US will be affected by ocean acidification by the year 2050. Riverine discharge, upwelling of naturally low pH waters and coastal eutrophication accelerate the impact. Social vulnerability is high in regions with either strong economic dependence on shellfish production, or low diversity of shellfish harvest and relatively low science accessibility (Ekstrom et al., 2015).

There is a small but growing body of literature aiming to assess the financial impact of ocean acidification (OA), mainly on calcifying species. Global assessment impacts of ocean acidification on molluscs suggest a loss of ~6 billion USD under constant demand and up to 100 billion USD, if the demand for molluscs increases with future income rise (this assessment assumes a 0.4 reduction in pH by 2100) (Narita, Rehdanz, & Tol, 2012).

The regional impact on Europe, while highly uncertain, is in the order of 1 billion USD by 2100 (Narita & Rehdanz, 2017). The highest levels of impact of OA on mollusc production are in countries with the largest current production, such as France, Italy and Spain, with extremely uneven impact across countries and their respective region (Narita & Rehdanz, 2017). In Denmark and the Netherlands, the largest losses are projected for mussels; in France, the largest impact is on oysters (Narita & Rehdanz, 2017). Overall, selective breeding of more resistant stocks (Parker et al., 2012), monitoring of the ocean pH, moving locations of mariculture and improved understanding of the biological response, are all likely to reduce the financial impact.

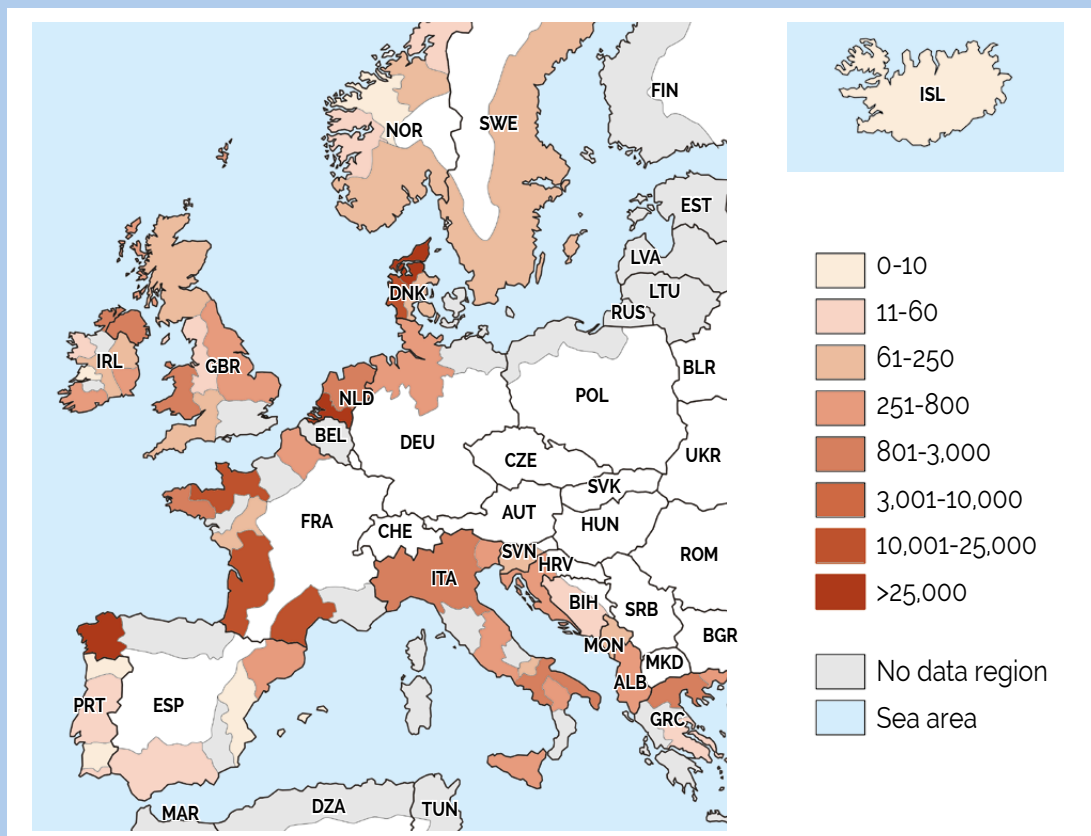


Figure 15. (Narita & Rehdanz, 2017; © Newcastle University). Estimated annual economic loss in sub-national regions of Europe in 2100 due to damages on mussel production under ocean acidification.

There is virtually no information about the impact of climate change on seaweeds and aquaculture. Many plants benefit from the high CO₂ by enhanced rates of growth and carbon fixation, and organic matter production (Zondervan, Rost, & Riebesell, 2002), suggesting that seaweeds may fare well under ocean acidification. Naturally-occurring hotspots of change, such as sites of marine heat waves, can provide insights into potential impacts (Schmidt & Boyd, 2016). Such marine heatwaves highlight that distribution patterns of seaweeds and demersal fish are highly impacted by temperature (Wernberg et al., 2013). Extreme marine heat waves resulted in a more than 100 km range contraction of the temperate kelp forest and a tropicalisation of the ecosystem, by the invasion of warm water seaweeds, invertebrates, corals and fishes (Wernberg et al., 2016).

Changing management approaches additional to the above-described monitoring of the pH can help reduce the impacts of ocean acidification on shellfish production. Combining production of seaweed with shellfish has the potential to have wide benefits. Cultivating seaweed generates habitat for fish, fertiliser and food for animals and humans, while reducing ocean acidification and its potential impacts on shellfish. The potential of highly-integrated systems of polycultures are discussed in more details in Section 3.2.8 (Integrated Multi-trophic Mariculture).

3.3.5 Aquaculture and wild catch in coastal systems strongly depend on the interaction with the land bordering the coast

Along the coasts, marine and land are strongly integrated systems. Food production in coastal systems strongly depends on the impact from the streams and rivers and, by extension, the land use in the catchment of these rivers (Wong et al., 2014). An increase in precipitation-driven flooding and the frequency of extreme events will particularly affect estuaries through enhanced river runoff, sediment loading and changes in nutrients and salinity. Many coastal ecosystems are built by foundational, habitat-forming species that are critical for supporting biodiversity and ecosystem functioning (Bruno & Bertness, 2001).

Increases in nutrient input can have both positive and negative impacts on the coastal system. On one hand, runoff provides nutrients for filter feeders. On the other hand, too much efflux changes carbonate chemistry in the coastal system and can lead to oxygen minimum zones. Oxygen deficiency is often increased by intense aquaculture.

The supply of larvae from the natural environment will be influenced by environmental impacts on coastal ecosystem engineers, such as corals, coralline algae and kelp, which also provide habitat for wild catch. Coral reefs, mangroves and seagrasses support coastal fisheries. Climate change has the potential to change the growth of these habitat-forming species (Melbourne, Griffin, Schmidt, & Rayfield, 2015), increasing their vulnerability to wave energy. Intense coastal aquaculture increases the degradation of coastal marine ecosystems, via the loss of mangroves (Ottinger, Clauss, & Kuenzer, 2016). A rise in sediment load can smother habitat-forming organisms (such as maerl algae), or decrease their fitness against predators (corals). As coral cover decreases,

which is predicted to be from 40% coral cover today to 10-20% by 2050, their ability to compete with seaweed for space will be reduced (Bell et al., 2013). The effects of global change on coastal macroalgae and seagrasses are much less investigated (Brodie et al., 2014) and possibly uncertain, given the regional distribution and features that superimpose with local anthropogenic impacts.

In the coastal environment, sea level and wave heights provide risks to the infrastructure of the aquaculture. Coastal habitats, especially very shallow ones such as lagoons, can be restricted due to human occupation, while sea level rise causes drowning of the existing ecosystems (Stutz & Pilkey, 2011). Aquaculture production is vulnerable to extreme events, such as storms and floods (Chang, Lee, Lee, & Shao, 2013). For example, shrimp farming operations in the tropics will be challenged by rising sea levels, which will be exacerbated by mangrove encroachment and a reduced ability for thorough drying of ponds between crops (Della Patrona, Beliaeff, & Pickering, 2011). Farming operations and facilities need to be 'climate-proofed' and relocated, if necessary.

3.3.6 Impacts of diseases, parasites and pathogens on increasing food production from the ocean

Diseases have large impacts on commercially-important species, such as salmon, molluscs and crustaceans, though the understanding of the effects of infectious disease in the ocean and their response to climate change is in its infancy (Burge et al., 2014). Current estimates predict that up to 40% of tropical shrimp production (>\$3bn) is lost annually, due to bacterial and viral pathogens (Stentiford et al., 2012). Industry-wide losses to aquatic animal diseases exceed US\$6 billion per annum (Stentiford et al., 2017). However, effective research and management resulted in some progress in identification, diagnostics, treatment and management of sea louse infections of the European Atlantic salmon (Groner et al., 2016).

Warming increases the multiplication of microbial pathogens, such as bacteria and fungi, and simultaneously stresses hosts, leaving them immunocompromised (Mydlarz, Jones, & Harvell, 2006). A good example of disease prevention has recently been propagated in Southeast Asia. Open flow-through intensive pond production has been replaced by integrated pond production of shrimp (using the same intensive systems as before), with pond recirculation systems with fish and aquatic plants. This creates a more stable microbial community that keeps the opportunistic *Vibrio* pathogens below the critical density, with more predictable production results (Robins McIntosh, pers. comm.).

Oyster fisheries have, in many cases, shown poor sustainability and collapsed due to diseases (Stentiford et al., 2012). As oysters accumulate marine bacteria, they potentially expose humans to large doses of harmful bacteria. *Vibrio vulnificus* is the most fatal foodborne pathogen in the USA, where it comprises 95% of all seafood-related deaths and has a fatality rate nearing 50%, even with aggressive medical treatment (Froelich & Noble, 2016). As temperature is one of the major driving forces

in determining bacterial concentrations, their abundance is predicted to increase with increased warming (Froelich & Noble, 2016).

There are many documented examples of the impact of different diseases on aquaculture. Winter warming is facilitating the spread of oyster diseases caused by *Haplosporidium nelsoni*, a necrosis virus. Extreme events are implicated in the outbreak of parasites *Perkinsus marinus*, which had an impact on the Eastern oyster (*Crassostrea virginica*). Summer mortality episodes in the Pacific oyster, *Crassostrea gigas*, have been associated with a complex association between pathogens (such as the herpes virus) and warming (Malham et al., 2009; Cotter et al., 2010). Milder winter temperatures may facilitate longer transmission periods and offer opportunities for the reproduction or production of more cohorts of parasites.

The nature and epidemiology of seaweed pathogens is under-studied. Changes in farm management practices, such as spatially close cultivation nets, make the crop more vulnerable to disease transfer and natural disasters. The illegal use of algicides/pesticides, with unknown detrimental consequences for the wider marine environment, may also negatively impact on the industry.

Not all diseases are likely to increase in prevalence and severity in response to warming. For example, salmon and sea trout in farms in Finland showed higher prevalence of some infections, but other diseases declined (Karvonen, Rintamäki, Jokela, & Valtonen, 2010). Breeding programmes have started to produce animals resistant/tolerant to several diseases to sustain shellfish production.

The increase in nutrients can support the formation of harmful algal blooms (HABs), a mass proliferation of toxic or nontoxic phytoplankton species. These neurotoxins are not destroyed by food processing and can only be detected through specialised laboratory testing (Deeds, Landsberg, Etheridge, Pitcher, & Longan, 2008; Berdalet et al., 2016; Turner et al., 2015). HABs affect either the invertebrate or vertebrate ingesting the toxins, as well as the humans consuming these food items. HABs cause economic losses in shellfish growing and collecting, in finfish production and in ancillary seafood industries. Outbreaks of *Pfiesteria*-like organisms in 1997 in Chesapeake Bay tributaries (in the USA) resulted in a collapse of seafood sales and a loss of \$43 million (Magnien, 2001). Annual estimated economic losses for the US are around \$20 million (Sanseverino, Conduto, Pozzoli, Dobricic, & Lettieri, 2016).

The causes of toxin production and apparent increase in HABs in recent decades, especially in areas where they have not previously been reported, are not fully understood (Trainer et al., 2013). They appear to be linked to anthropogenic pressures in coastal areas, with oxygen depletion being one of many triggers. As each phytoplankton species is typically adapted to grow over a range of temperatures, global warming may also be responsible for the changing pattern of dinoflagellate blooms (Sluijs & Brinkhuis, 2009).

New biotoxins are continually identified, which pose challenges for monitoring and management procedures (Turner et al., 2015). Enforced periodic closures of commercial

harvesting or growing areas are currently the only effective way to protect human health. Information on the extent of mortality on phytoplankton and zooplankton is extremely limited, when compared to species of economic interest. However, this information is of paramount importance for understanding how planktonic food webs can respond to climate change.

3.3.7 Microplastics have an unclear range of impacts on food production from the ocean

Among pollutants, microplastics, fibres and particles <1mm, are a growing concern for marine ecosystems. Plastic production from synthetic fibres has increased by 61 Mt (Lusher, Hollman, & Mandoza-Hill, 2017). In 2010, between 4.8 million to 12.7 Mt of plastic waste entered the oceans (Lusher et al., 2017). Microplastics are globally present and can be found in the gastrointestinal tracts of species (Lusher, McHugh, & Thompson, 2013). Ingestion of microplastics by species of commercial importance for fisheries and aquaculture has been documented in laboratory and field studies (Lusher et al., 2017). Microplastics have been observed in fish, mussels, clams, oysters and scallops. The plastic content was higher in omnivorous fish than in herbivorous or carnivorous species (Mizraji et al., 2017).

Microplastics contain a mixture of chemicals added during manufacture and adsorb or absorb bioaccumulative and toxic contaminants (Lusher et al., 2017). Microplastics can harbour pathogens, increasing the risk of disease and loss in the aquaculture of molluscs, crustaceans and fish. Bacteria in the genus *Vibrio* have been found on microplastics drifting in the North Atlantic subtropical gyre (Zettler, Mincer, & Amaral-Zettler, 2013).

In oysters (*Crassostrea gigas*), ingestion of microplastics during gametogenesis had negative impacts on feeding and reproduction, adult fecundity and offspring quality (Sussarellu, 2016). Assessment of *Mytilus edulis* and *Crassostrea gigas* showed accumulation of microplastics, resulting in loads of 0.36 ± 0.07 particles/g mussel and 0.47 ± 0.16 particles/g of oyster (Van Cauwenberghe & Janssen, 2014). Adverse effects have only been observed under laboratory conditions and high exposure that exceed present environmental concentrations, by several orders of magnitude (Lusher et al., 2017).

Data on microplastic contamination of seafood products, particularly edible tissues, is very limited, thus the risk of microplastic consumption on human health is unknown (GESAMP, 2016).

3.3.8 Increasing seaweed consumption has significant uncertainties with regards to food safety

Seaweeds have been traditionally harvested for centuries, often linked to local cultural identities, although only a small number are commercially utilised (Mac Monagail, Cornish, Morrison, Araújo, & Critchley, 2017). Today, 32 countries actively harvest seaweeds from wild stocks. Overexploitation of natural seaweed resources could

lead to significant ecological, economic and social consequences at local, regional, and global scales.

Upscaling algal culture has a number of uncertainties. Sufficient production has to meet the needs of people, but also their preferences. Possible risks associated with algal food consumption include allergenic potential, excess intake of toxic metals, biotoxins and various secondary metabolites (e.g., prostaglandins, kainoids), as well as contamination with pathogens, radioisotopes, and other toxic synthetic compounds (Wells et al., 2017). Algal culture and its potential are discussed in detail in 3.2.3.

The nature and epidemiology of seaweed pathogens need to be better understood to upscale production and species in culture. As the seaweed aquaculture industry grows and diversifies into new species and geographical areas, new diseases are likely to emerge. Protocols used to mitigate crop losses are rudimentary and often costly for small farmers and co-operatives. Changes in farm management practices, such as placing the cultivation nets closer together, make the crop more vulnerable to disease transfer and natural disasters. It is important to implement early disease detection systems and to build capacity within the sector (Loureiro et al., 2015).

There are still large uncertainties about nutritional benefits or the potential for health risks. Although there is strong evidence for the health benefits of a wide range of algal-derived food products, more clinical research is required to quantify the health benefit of these food products, to assess potential adverse effects and to understand the digestibility of them. Macroalgae are very rich sources; however, the absorption rate from macroalgae is slow, facilitating a typical eastern/Japanese intake which is around 1-3mg/capita/day (Zava & Zava, 2011). Most seaweeds contain too few available calories via human digestion for complete nutrition (Cornish, Critchley, & Mouritsen, 2015) because the polysaccharides, which are the predominant component (76 % of the total dry weight, and typically ~50 %), are not digested to any great extent in the gut. They comprise structural (celluloses, hemicelluloses, xylans) and storage polysaccharides (alginates, carrageenans and agar, depending on the type of seaweed). There is also considerable uncertainty surrounding the nature of the interaction between human metabolism, the composition of the individual's gut microbiome, the algal food (Wells et al., 2017) and the effects of food processing. Dietary fibre and phenolic compounds, which react with amino acids to form insoluble complexes, may decrease nutritive values and reduce digestibility (Mišurcová, Kráčmar, Klejdus, & Vacek, 2010; Wong & Cheung, 2001; Tibbetts, Milley, & Lall, 2016). Food processing, disrupting cellulosic cell walls, may improve digestibility and widen the range of digestible seaweeds.

3.3.9 Engineering the climate will impact the ocean – the direction of which is unclear

A range of geoengineering options have been suggested to intentionally modify the Earth's climate on a large scale and which involve the ocean. The methods suggested differ in their main mode of intervention, whether it be solar radiation management or carbon dioxide removal (IPCC, 2012). Techniques include increased crops, large-scale

afforestation, coastal blue carbon storage, enhanced ocean productivity, increased weathering, carbon capture and storage to cloud treatment for solar radiation management (Williamson, 2016). We know very little about how each of the carbon dioxide removal (CDR) and solar radiation management (SRM) methods might modify ecosystems and their associated services, as there have been few studies on CDR and none on SRM methods (Russell & Connell, 2012). Analyses of the effects of SRM on oceanic photosynthesis by phytoplankton have not been made, for example (Russell & Connell, 2012), and SRM does not alleviate the impacts of ocean acidification.

Carbon dioxide removal methods involve iron fertilisation, (changing the biological pump or direct injection of CO₂), into either the ocean or the underlying sediments. Major uncertainties exist regarding the effects of these techniques on the physical climate system and on biogeochemical cycles, their possible impacts on human and natural systems, and their effectiveness and costs (IPCC, 2012).

The injection of CO₂ into submarine geological structures has the potential to create leakages of the CO₂ back into the marine environment (Rastelli et al., 2016). At very low pH treatments (5.5) close to the leakage site, significant mortality in macrofauna and nematodes causes changes in community structure and diversity reduction at 20 weeks' exposure (Widdicombe et al., 2009). After 60-day exposure to pH 6.5, the tissues of *Mytilus edulis* are not impacted, though elevated calcium ion levels indicated that the health of the specimens was affected (Beesley, Lowe, Pascoe, & Widdicombe, 2008). Similarly, *Arctica islandica* has been shown to tolerate pH reduction to a pH of 6.2 (Bamber & Westerlund, 2016), values one would associate with leakage from the injection system.

Changes in the micronutrient supply to oceanic plankton are thought to have a significant effect on the concentrations of atmospheric carbon dioxide, by altering rates of carbon sequestration in areas where macronutrients are sufficient but primary productivity is low (Boyd et al., 2000). The increased primary productivity would decrease CO₂ and hence ocean acidification. If exported into the deep ocean, the process would store this CO₂ over geological timescales, but would also increase the decay of organic matter in the deep ocean, causing acidification (Cao & Caldeira, 2010). Experiments show an increase in diatom production but no export into the deep ocean (Boyd et al., 2000). As such, they would increase carbon at the base of the food web. At the same time, the growth of the toxigenic diatom genus *Pseudonitzschia* raises concerns because it produced neurotoxins (Trick et al., 2010). Additionally, the remineralisation of the organic matter at shallow depth would increase oxygen drawdown. Large-scale increase of productivity in one region could have unknown impacts and could reduce the yields of fisheries elsewhere.

Two main methods of increases in nutrients and hence primary production have been suggested.

Firstly, artificial upwelling of water from deeper parts of the ocean (Oschlies, Pahlow, Yool, & Matear, 2010). Such water would also increase surface ocean acidification, impacting ecosystems (see Section 3.3.1).

Secondly, artificial weathering of rock, with the addition of calcium oxide to the ocean, would change the ion composition of the ocean. It is a very costly process, with a large environmental footprint (Russell & Connell, 2012). Ignoring the energy needed to deploy the infrastructure for these intervention, and the associated disruption of the marine system that would occur, similar questions as associated with ocean fertilization would arise.

More controllable, seaweed aquaculture beds combine nutrient removal and CO₂ assimilation (Sondak et al., 2016). In 2014, the total annual production of Asian-Pacific seaweed aquaculture surpassed 2.61×10^6 metric tonnes, with an annual carbon accumulation equivalent to over 2.87×10^6 t CO₂/y (Sondak et al., 2016). Expansion of these beds would result in competition for space with other coastal aquaculture and, at the same time, some seaweeds could be used in feed or food for humans. Furthermore, expansion in this economically valuable area would have to be managed carefully.





4. The market and social response to new challenges

Introduction

Options to increase the productive capacity of food production need to be considered in a comprehensive way. We cannot answer the specific question of how to obtain 'more' from a bio-economic perspective only, but must also consider ethical choices and normative values, social impacts and governance changes. A sustainable way forward must consider societal support for how we can best use the resources available to us.

The socio-economic perspectives are presented in Chapter 4, in three sections. Fishing and mariculture involve questions of food preference, market availability and access, as well as democratic processes of addressing change and challenges, with citizens' participation. The first section (4.1) highlights the general consensus of social scientists around the rights-based management approach as the path towards the sustainable growth of fisheries over time, and the most profitable method for long-term revenues and production. The section presents different strategies by which to implement such an approach, all currently in use, but some far more developed in Europe and others considered less efficient for European needs. However, this approach still faces strong social problems; Section 4.2 therefore presents the argument for an improved 'bottom-up' approach of stakeholder consultation and public acceptance. This section also outlines the need for developing new markets, improved information on seafood labelling and encouragement of smarter eating of lower trophic level fish. The third section (4.3) addresses ocean governance issues, requiring a multi-level approach, from regional or sub-regional, to global. The section also suggests that a policy of incentives and rewards for sustainable fishing needs to be considered, to replace the obsolete system of subsidies.

4.1 WHAT ARE THE CURRENT AND ANTICIPATED FUTURE COST-EFFICIENCIES OF VARIOUS TYPES OF PRODUCTION ALTERNATIVES?

In examining how to obtain 'more', we must consider the tension between availability and affordability. We must weigh up whether there is demand for 'more' in existing markets and the effects of supply increases on those markets. We must estimate the extent to which the issue of 'more' can be addressed by creating new markets for species not currently seen as commercially viable. In this, we need to be able to account for the impact of cultural preferences, both on existing markets and on the development of new markets. Currently, the Common Fisheries Policies (CFP) explicitly discourages the creation of new markets for by-catch (in particular, for undersized and unwanted species). The CFP presents general considerations and guiding principles

that are relevant to small-scale fisheries, but the relevant 'social objectives' are imprecise and the CFP is not considered to be an instrument of social policy nor indeed of food security. Future decisions about food from the sea must balance temporary social and monetary benefit, and industrial production, with long-term economic and social benefits, and healthy living. However, values are not universal and are related to specific conditions. Policies must be relevant and acceptable across many different geographies and socio-cultural contexts.

In the following section, we focus on cost-efficiencies, in particular, challenges such as:

- The tension between availability and affordability;
- Whether there is demand for 'more' in existing markets and the effects of increased supply on those markets;
- The extent to which the issue of 'more' can be addressed by creating new markets for species not currently seen as commercially viable.

4.1.1 What are efficient production alternatives for wild capture fisheries?

Total allowable catches remain too high worldwide. Current trends of increasing demand and increasingly efficient fishing technology are set to lead to overfished stocks and decreasing global catches (Costello et al., 2016; Quaas, Reusch, Schmidt, Tahvonen, & Voss, 2016). Several studies show that a temporary reduction of catches not only increases physical yield from recovered stocks, but also the economic profitability of fisheries (Costello et al., 2016; Quaas et al., 2012; World Bank & FAO, 2008).

A recent study estimated the benefits of achieving maximum sustainable yield (MSY) for EU Northeast Atlantic fisheries (Guillen et al., 2016). This would entail a reduction in fishing effort (proportional to fishing mortality) by 38%, which would result in the following:

- Value of landings would increase from EUR 4.52 billion to EUR 7.12 billion;
- Costs of fishing would decrease from EUR 4.41 billion to EUR 2.73 billion;
- Gross Value Added would increase from EUR 1.8 billion to EUR 5.76 billion;
- Operating profit would increase from EUR 0.10 billion to EUR 4.91 billion.

Guillen et al. (2016) estimate that it generally takes about 20 years for stocks to fully recover, but that large benefits (e.g. 90% of MSY yields) would be achievable already after the 6th year. An increase in profits would be almost immediate (about EUR 2 billion), even though this would be primarily from reducing the costs of fishing. The authors estimate that EUR 2.25 billion is needed for a vessel buy-back scheme, to reduce vessel numbers from 27,081 to 10,291.

However, it is important to bear in mind that much-reduced fishing effort requires that compliance management is in place and regular assessments are undertaken. While some of the European fisheries are well-managed and recovering, there are overfished regions and stocks. Further analysis needs to focus on regional contrasts,

as most overfished stocks globally are those without proper assessment in regions with low capacity for assessment and management (Fernandes et al., 2017).

Among economists, there is wide agreement that rights-based management leads to higher quality fish, better selection for age classes and species, and smoothing out supply over time. Rights-based management is typically based on individual or pooled fishing rights that reduces the 'race to fish' by allowing the rights-owner (individual or collective) to distribute fishing effort according to expected abundance. These effects are very beneficial for food security, suggesting that rights-based fishery management could be useful for increasing food from the ocean. Even more, they are economically beneficial, almost doubling the profitability of fisheries compared to the current level (Costello et al., 2016).

However, a rights-based system in fisheries works only if effective catch restrictions and compliance monitoring are set in place by the regulating authorities. Moreover, rights-based systems such as Territorial Use Rights in Fishing (TURF) or Individual Transferable Quota (ITQs) may lead to a restructuring of fisheries that is perceived as socially undesirable, both in terms of increasing inequality among fishermen and in terms of concentrating fisheries in fewer ports (Grainger & Costello, 2016). Regulating fisheries by means of catch taxes (Weitzman, 2002; Jensen & Vestergaard, 2003) or annually-auctioned fishing permits (Bromley, 2009) may mitigate these issues, whilst maintaining the benefits of a rights-based fishery management. Wider concerns of long-term precautionary harvesting and social imbalances will be discussed in Section 4.2.

The last reform of the European Common Fisheries Policy (CFP) has enacted a landing obligation, or discard ban, for European fisheries. The purpose of the landing obligation is to decrease bycatch by making it more tedious to fishers. The CFP is clear that the landed bycatch (former 'discards') may not be used for human consumption and may not lead to the creation of new markets. This is currently considered best practice in Europe. However, scholars seem to disagree on this practice. On the one hand, the landing obligation is likely to increase the amount of fish that is landed from the total catch. A full implementation of the policy will thus increase the fish available for fishmeal/fish oil. In addition, the landing obligation increases the incentive to fish selectively to increase the composition towards valuable catch, and thus can contribute to reduce bycatch of undersized or under-aged fish of the same or other species. This effect increases the future yield from these stocks. On the other hand, if bycatch is reduced to fishmeal and oil, this practice might discourage the creation of new markets.

The landing obligation has applied to the Baltic Sea, among other areas, since January 2015, although its enforcement is lagging behind. The main reason is the large effort required to monitor and control the regulation. A more rigorous implementation of the discard ban could make a significant contribution to obtaining more biomass and food from the ocean, although this needs to be combined with encouraging the consumption of a broader range of species.

4.1.2 What are efficient production alternatives for mariculture?

Mariculture (marine-based aquaculture) is often mentioned as the fastest-growing food production sector globally (Asche, 2008). However, as stated above, this growth is from a very low base.

The costs of marine aquaculture production have fallen in recent decades, with improved feed conversion ratios, better feeding technologies, the development of oil-based vaccines, improved site location decisions and more advanced sea cage systems. Feed composition will need to continue to evolve in response to the price volatility of different feed inputs and in response to greater environmental stewardship demands by consumers. Continued research that reduces the marine input in feed should facilitate more sustainable growth in marine aquaculture and potentially a net increase in production.

A recent study (Blomeyer & Sanz, 2017) prepared for the European Parliament states:

Potential development of the aquaculture sector can be assessed based on the Future Expectations Indicator (FEI), which indicates whether the industry in a sector is investing more than the depreciation of their current assets. With DCF data from 19 countries (excluding Poland), the FEI for the EU aquaculture sector was estimated to be negative at 5.8% in 2014. This is a decrease from the 3% reported in 2012 (STECF 2016b). This appears to show negative expectations on the future development of the sector, but this masks both positive and negative expectations, depending on the sector and the MS, as well as high variability between years since some major investments (e.g. vessels) do not occur frequently.

Integrated Multi-Trophic Aquaculture (IMTA) has been put forward as a production method that could help resolve the apparent conflict between the growing demand for seafood and environmental concerns (Jeffery et al., 2014; see above). In an IMTA system, several species are combined in the production process, selected by their function in the ecosystem, the relationship to each other and their economic value. Species are combined to facilitate nutrient cycling and decreased nutrient outflow. IMTA can diversify the economic risks of fish farmers by generating income from a wider variety of marine species such as lobsters, sea cucumbers, mussels, oysters, scallop, abalone, crabs and seaweed, rather than just a single finfish species, which is the approach followed in traditional marine aquaculture situations (Barrington, Chopin, & Robinson, 2009). Chopin, Cooper, Reid, Cross, and Moore (2012) point out that profitability may be increased further if production costs are kept lower through joint species production methods, such as IMTA with improved nutrient cycling, or if consumers are willing to pay a price premium for aquaculture products with lower environmental impacts. However, while IMTA is successful in China, it has not been proved commercially to date in Europe. The future role of China, both of its exports and its impact on coastal modification, as well as its impact in the food production, requires a more in-depth analysis than what could be included in this report.

A key aspect of investment in IMTA will be determined by the extent to which consumers are willing to pay higher prices for the variety of fish and shellfish produced using this more sustainable form of production. Results from the European-funded project IDREEM have suggested that consumers across the EU might be willing to pay a price premium for IMTA-produced seafood (van Osch, Hynes, & O'Higgins, 2017; Bell, Rothlisberg, & Munro, 2005). While IMTA could result in more sustainable forms of mariculture, a key question remains as to whether the skillset required for multi-species fish farming exists or whether new training and education programmes are needed and also, in terms of governance, whether new licensing systems would need to be designed for IMTA processes.

Some types of finfish farming include tuna farming in the Mediterranean, farming of European eel (predominantly in the Netherlands), and farming of milkfish in the Philippines (Arceo, Cazalet, Alino, Mangialajo, & Francour, 2013). These fish farms rely to a large extent on raising juvenile fish from wild-capture fisheries. Thus, expanding this type of aquaculture will increase the pressure on wild-capture fisheries (Regnier & Schubert, 2016) and therefore the policies developed to encourage greater production need to account for the degree of interconnection between these forms of production and the integration of product markets. One such policy is to retire commercial quotas equivalent to the catch of juveniles used for on-growing, taking into account growth and natural mortality (Bell et al., 2005).

Some forms of mariculture have benefits beyond food production. Filter feeders such as blue mussels have positive environmental effects, as they remove algal biomass, flocculated organic particles and sediments from the water. If this extra benefit is taken into account through remuneration, mussel farms may become profitable, even for the supply of fishmeal or fish oil.

4.1.3 Other food and biomass

The oceans also have a large potential in producing plant-based food and biomass, for example, from macroalgae (Santelices, 1999; Werner, Clarke, & Kraan, 2004; Troell et al., 2009; Kraan, 2013; Lorbeer, Tham, & Zhang, 2013; Buschmann, Varela, Hernández-González, & Huovinen, 2008; Rebours et al., 2014; Skjermo et al., 2014; Hafting et al., 2015; Kim, Yarish, Hwang, Park, & Kim, 2017). Such products may be used directly for human consumption, or indirectly, as animal feed in aquaculture or livestock farming. Another channel may be biomass/bioenergy production from macroalgae, which may alleviate the pressure on farmland over the coming decades, if the Paris climate goal is pursued (e.g. Kraan, 2013; Chung, Beardall, Mehta, Sahoo, & Stojkovic, 2011; Chung et al., 2013; Wei, Quarterman, & Jin., 2013; Sondak et al., 2016). Mariculture of macroalgae is most suited to shallow sheltered waters as waves and swell, in addition to high current velocities, may cause damaging acceleration on both the infrastructure and the cultured species (Troell et al., 2009). Experimental studies in the North Sea indicate the potential for algal mariculture in more exposed offshore waters, using a novel ring construction (Buck & Buchholz, 2004; Buck, Nevejan, Wille, Chambers, & Chopin, 2017). In a recent review, Van den Burg, van Duijn, Bartelings, van

Krimpen, & Poelman (2016) concluded that, based on current available information, offshore seaweed production in the North Sea is not economically feasible and that to be profitable, revenues would need to increase by about 3-fold.

4.1.4 If production is to be increased, how can one overcome difficulties?

Key differences exist in production between wild fishing and marine aquaculture. In particular, the fishing industry does not *produce* fish, it only *harvests* fish and therefore it must consider the production capacity of nature. So too with many aspects of mariculture, where the wild ecosystem may provide spat or juveniles for culture, high-quality water, processing of waste and, in the case of filter feeders and carnivorous fish, all or some of the food source. While there are natural constraints on the capacity for increases in production, we need to consider the social and economic constraints, which could limit the potential. The economic constraints include issues around investor attitudes to investment in 'old industries', where there are competing investment opportunities. We also need to consider where poor regulatory environments impose a major constraint.

4.1.5 Economic constraints on investments

For wild-capture fisheries, there will be a need for 'investment' to increase long-term yields during a phase of reduced catches as stock are rebuilding. During this investment phase, fish consumption and employment in the fisheries have to go down. However, the long-term economic net effect of rebuilding overfished stocks is positive and large (World Bank & FAO, 2008; Quaas et al., 2012; Costello et al., 2016).

The growing literature on individual transferable quotas (ITQs), and on intensive salmon aquaculture and its negative impacts on the environment and other users of related marine space, has been little connected to the developing literature on financialisation and to the literature on ocean-grabbing within fisheries. Knott & Neis (2017) seek to address this gap through a case study of the recent history of herring fisheries and intensive aquaculture in New Brunswick, Canada. The study explores how specific neoliberal processes – including privatisation and marketisation (in herring fleet ITQs and aquaculture lease systems), (re)regulation, financialisation and globalisation – have interacted to support the reshaping of regional fisheries, from mixed small-scale, family-based, petty commodity fisheries towards vertically-integrated, corporate, financialised fisheries characterised by ocean-grabbing.

Start-up conditions for new mariculture production in Europe are in general difficult and, in some cases, very difficult. Capital is needed to start new activities, but banks and other investors are holding back. This again seems to be directly linked to licensing procedures. Less-intensive mariculture struggles with productivity, compared to alternative proteins. There is consensus among the experts that the appropriate approach for facilitating start-up investments is to set up clear, transparent, and harmonised regulation and rules, according to which an aquaculture firm will get licensed.

Some Mediterranean countries in EU Member States have burdensome procedures that present considerable risk (time, cost, unpredictability of outcome) that put off investment to develop new production sites. Other countries (e.g. Mediterranean North Africa) have little or no legislative framework, which presents a considerable risk to the outcome.

Consumer responses to wild and farmed fish production depend on the degree of market integration (Anderson, 1985; Jensen, Nielsen, & Nielsen, 2014). Numerous empirical studies on market integration between wild-caught and farmed fish find mixed results (Asche, Gordon, & Hannesson, 2002; Nielsen, 2005; Virtanen, Setälä, Saarni, & Honkanen, 2005; Asche, Guttormsen, Sebulonsen, & Sissener, 2005; Nielsen et al., 2007; Norman-López, 2009; Nielsen, Jensen, Setälä, & Virtanen, 2011; Asche, Benneer, Oglend, & Smith, 2012; Bronnmann, Ankamah-Yeboah & Nielsen, 2016). Yet most studies find that markets for the same species of fish, whether appearing from fisheries or aquaculture, are integrated. This theoretically implies that profitability of fish farming depends on the status of the wild capture fishery and vice-versa. In reality, we are not aware of a single significant and substantial example where mariculture of a marine species has reduced fishing pressure.

4.2 SOCIETAL RESPONSE TO INCREASED PRODUCTION

The global ocean seems vast but is increasingly congested and intensively utilised. In the inshore and coastal areas, industrial sectors are in competition for access and space. Is the coast to be used for the purposes of tourism, conservation habitats, mariculture or wild-catch? The process of 'urbanisation of the ocean' produces pressures on marine habitats and has consequences for human coastal communities.

4.2.1 Public response/perception

Mariculture or farmed fish production is one alternative to meeting the increasing demand for the production of fish. However, public perception of farmed fish products varies, especially in the Western world. In the 1990s, Anderson and Bettancourt (1993), Gu and Anderson (1995) and Holland and Wessells (1998) reported evidence that consumers prefer farmed fish over wild fish. However, as aquaculture production increased, more attention was given to the environmental effects of the production process, which creates negative externalities (Naylor, Goldberg, Primavera, & Kautsky, 2000). Over this time, consumer attitudes have shifted to a preference for wild fish (Salladarré, Guillotreau, Perraudeau, & Monfort, 2010; Roheim, Sudhakaram, & Durham, 2012; Uchida, Onozaka, Morita, & Managi, 2014, Bronnmann & Asche, 2017). While this in itself constitutes a challenge for farmed seafood, the fact remains that maricultured and wild seafood within a species group are highly substitutable. There have been some attempts to mitigate these challenges, by labelling farmed seafood as organic or using best practices labelling (Asche, Larsen, Smith, Sogn-Grundvåg, & Young, 2015; Ankamah-Yeboah, Nielsen, & Nielsen, 2016). However, these are at best halfway measures, since they are only imperfectly addressing the sustainability and food quality concerns. Overall, the empirical literature on the interaction between the

markets for wild and farmed fish shows that consumers need trustworthy information about production processes and the environmental consequences of fish farming. Only then will it make increased supply from aquaculture acceptable to them (Bronnmann et al., 2016; Chidmi, Hansson, & Nguyen, 2012; Dey, Rabbani, Singh, & Engle, 2014; Roheim, Sudhakaran, & Durham, 2012; Sha, Santos, Roheim, & Asche, 2015; Singh, Dey, & Surathkal, 2014; Xie, 2015; Bronnmann et al., 2016).

Furthermore, several studies show that the demand for wild species is more elastic than the demand for species from aquaculture, and also farmed fish demand is rather elastic (Asche, Roll, & Trollvik, 2009). In socio-economic terms, the value of food from the ocean to consumers is more important than the volume of edible biomass harvested. A price-elastic market implies that the seafood industry still has the potential for growing revenues, if production increases (Asche et al., 2005). This may lead to the conclusion that the market potential for farmed fish is not yet fully developed. This is important, as it indicates that it is still possible to create market niches for farmed, as well as wild products.

Numerous studies have examined attitudes to seafood production in recent years (Mazur & Curtis, 2006; Schlag, 2010; van Osch et al., 2017). As pointed out by Freeman et al. (2012), there has been evidence of confusion among the public regarding the information they receive on seafood products. In one of the most comprehensive surveys ever carried out on attitudes to seafood amongst consumers, a recent Eurobarometer study (EC, 2017) aimed at increasing the level of knowledge of what EU consumers look for and what factors determine their purchase of seafood. It involved a public survey of approximately 28,000 citizens across all EU member states. At EU level, the majority of citizens were found to eat seafood at least once a month but there are important differences between countries and age groups. In Spain, for example, seafood is generally consumed at least once a week, while in Hungary, eating seafood even once a month is unusual. It was also found that older consumers have a higher frequency of eating seafood. The survey instrument also tested whether consumers have any preference regarding wild and farmed fish products and found that while consumers in general prefer wild products, a large share of consumers have no specific preference. This reflects the fact that consumers pay more attention to other aspects such as quality, price and origin. The study also tested the relevance of voluntary information on packaging and found that the date of catch or production is clearly relevant to consumers. Environmental information was found to be relevant in some countries but not across the entire EU. These findings are in line with earlier studies, which revealed a list of ten attributes that consumers look for when buying seafood (see below Table 4.1 and Skjelvik, Bremer, Hauge, & Kaiser, 2012).

Common attributes influencing consumer evaluation of food relative to their values (in no particular order)

- i.** Sensory attributes (taste, smell, texture...);
- ii.** Health and nutrition;
- iii.** Cost;
- iv.** Convenience;
- v.** Degree of satiety (feeling of fullness);
- vi.** Food safety;
- vii.** Animal welfare;
- viii.** Environmental sustainability;
- ix.** Sharing a nice meal with family or friends;
- x.** Fair trade

Table 4. (Bremer, Haugen, & Kaiser, 2012). Deliverable 8.8: European consumer perspectives on seafood from aquaculture: a review of consumer values, knowledge and perceptions.

However, the preferences of consumers buying their dinner do not necessarily reflect more general attitudes, which may come to have a bearing on policies or on specific market segments. Again, the situation is divided across Europe. In some countries, one observes a marked negative attitude towards aquaculture in general or specific segments of mariculture, promoted by environmental organisations or parts of the media. Typical issues of concern are animal welfare (for example, 'how many individual fish are in one cage?'), use of antibiotics and other chemical substances, and pollution to the environment. Some organisations have started certifications (W/WF, n.d.; Naturland, 2015). There are competing versions of sustainability among different environmental and conservational NGOs. In the end, public perceptions are built on trust towards the information source. In regards to information on food issues in general, trust in governmental agencies seems limited, given a history of contradictory experiences.

Consumer attitudes towards established, as well as new wild or mariculture products, may be difficult to influence by information campaigns alone. Trustworthy information sources are required. However, if the end product is seen as fulfilling certain qualities, the product could be successful on the market. This may be true, for example, if the production is within a short value chain such as a regional product for locals and the tourist industry, like in the case of small-scale fisheries.

AsAsche (2011) points out, while biomass production may not be severely reduced when a fish stock is significantly fished down, the new species that replace the overfished stock are often less desirable to consumers and therefore the value of the harvest of the new species will be less, if fished at all. Making these 'new species' more desirable to consumers could be a way to increase food from the ocean. However, except for a few case studies, there is no scientifically-established approach to achieve this goal.

Stakeholder and market acceptance is not necessarily straightforward and is based on various factors, which differ between countries and regions (Alexander et al., 2016).

The introduction of new species in mariculture is obviously largely a cultural issue, depending on customary food habits. Some species low on the food web (e.g. algae or jellyfish) may be acceptable to Asian consumers, but are viewed as exotic and unattractive in Western countries. This may, in the future, be overcome by more selective breeding and more refined food processing industries. Currently, nearly all lower trophic species lack a more sophisticated market image.

4.2.2 Corporate social responsibility: what social licences to operate may be envisaged?

The term 'social licence' is defined by Moffat and Zhang (2014) as the ongoing acceptance and approval of a development – such as a business enterprise – by local community members and other stakeholders. Social licensing can affect profitability and other outcomes (see also Thomson & Boutillier, 2011; Moffat, Lacey, Zhang, & Leipold, 2016). In regards to wild or farmed fish operations, a social licence to operate (SLO) stresses the central importance of obtaining public acceptance of bio-economic activity. While social licence to operate emerged in the discourse from several industries (for example, the mining industry) in the mid-1990s, it is still a relatively new term in marine resource use.

Thus, more emphasis on broad cooperation in innovation and societal responsibility is needed. This would represent a shift towards a systemic, open and user-centric innovation policy. Indeed, linear, top-down, expert-driven development, production and services is giving way to different forms and levels of co-production with consumers, customers and citizens. This also sets a challenge for public authorities and the production of sustainable marine biomass. Some of these challenges are more connected with enterprises, others with universities, public organizations and users. In this way, the term 'social licence to operate' addresses a huge cultural change – be it in the public or private regime, and along the entire food production chain.

From the consumer's perspective, the implicit values of the 'choice editors' of retail chains may be a case in point. Large food corporations play a decisive role in determining the sourcing and provisioning of the food market and must develop further their public responsibility for sustainable marine foods. Industrial actors along the value chain of seafood need to identify crucial nodes of social responsibility and integrate adequate consultation. In this way, the private sector would develop and strengthen its share of responsibility in sustainable marine food production. Decision-support tools spanning economic, socio-cultural and ethical issues should be utilised and co-developed with users, as an integrated part of a revised corporate social responsibility (CSR) approach.

An example of marine resource planning and use (including fishing and aquaculture), in which social engagement was deliberately introduced to achieve public acceptance of the outcome, comes from New Zealand. Here, over a four-year period, the Sea Change project (Sea Change, n.d.) developed a marine spatial plan for the Hauraki Gulf

Park, a large embayment and outer coast (1.2 million ha) on the east coast of North Island, important for commercial, recreational and customary fishing, aquaculture and marine recreation. The plan (see e.g. Sea Change, 2017) was produced by a multi-sector stakeholder working group (SWG), after extensive community and Māori tribal (Iwi) engagement and with input from local and central government agencies, and from science experts. The effectiveness of the social engagement led by the stakeholders themselves will be seen over the next few years, as the spatial plan is put into operation. This process of stakeholder-led spatial planning and wide community engagement, rather than governmental or institutional led initiatives, could serve as a model for similar processes in European settings.

The main motivation to include various forms of knowledge, tools and instruments in the context of SLO and CSR is based on the insight that successful and applicable solutions of many environmental and social problems, such as maintaining and promoting sustainable marine food production, must reconcile actors and natural processes at the local, regional, national, and global levels (Krause & Welp, 2012). To foster, improve and maintain SLO, social learning can be regarded as an essential element of policy development and implementation. Indeed, science, policy, public and commercial industries all have to be included in processes that take place in our economies, environment and societies which, in turn, will affect the outcomes of Blue Growth initiatives and the associated SLO.

To generate and maintain legitimacy, new instruments are needed that focus on open innovation co-production of knowledge, consensus-building and social responsibility on multiple levels. Under this umbrella, transparent and ongoing communication of legitimacy on the question – who decides what, when, and what will be the likely short- to long-term consequences and trade-offs – must be addressed. An increased focus on SLO in a long-term implementation framework is likely to generate long-term benefits, both in terms of consumer confidence and reliable conditions for start-ups.

4.2.3 SMART Eating

The consumer makes the choice of the 'right' food under given constraints (affordability, cultural traditions, religious constraints, ethical judgement e.g. about animal welfare). Retailers, including a few very large corporations, source and provide food in globalised chains. Governments provide sophisticated assessment tools, including risk and ethical assessments that accompany the development of the food market.

One promising way forward seems to be what we might call *SMART Eating*, by matching information to consumption. Ecolabelling, including information about species, production and consumption advice might be made available to the consumer in a more transparent and systematic way than is currently the case. Such information could be tied to new and engaging narratives, not weaved around economic benefits alone, but adapted to societal values and the plurality of users and traditions. An example of such an intervention is the *Food Smart Cities* initiative, funded by the EU in collaboration with a range of major cities (Milan Urban Food Policy Pact, 2015). A major

insight in this project is that decentralised cooperation to tackle global issues locally may be a way forward. The wider impact of such initiatives is too early to assess.

SMART Eating initiatives are likely to face issues related to the full compass of food security as alluded to in the introduction to this report. These are issues of sufficiency (food that meets the needs and preferences of people); safety (food that provides nutritional benefit while posing minimal health risks); sustainability (food now and for future generations); shock-proof (resilience to shocks in production systems and supply chains); soundness (food that meets legal and ethical standards for welfare of animals, people and environment); and perhaps most importantly, issues of accessibility and affordability.

4.3 WHAT GOVERNANCE ARRANGEMENTS CAN HELP ENSURE SUSTAINABLE HARVEST OF INCREASED MARINE PRODUCTION?

The main question in this chapter is about governance – how existing, strengthened or novel governance arrangements can help ensure the sustainable harvest of increased marine production. Governance is not government, but rather describes modern methods of societal steering that involve public and private actors, crosses levels of public policy (from local through to global), and includes decentralised and centralised modes of steering (Biermann, 2014). Regarding ocean governance, one defining characteristic is that vast parts of the area to be governed are beyond national jurisdictions, and that the legal and political regimes governing human activities are complex, fragmented and at times still contested, and that compliance control is difficult.

The policy context in which Europe is operating is the Maritime Space Planning (MSP), that facilitates the process of efficient management to avoid conflict and create synergies between the different sectors and uses of the marine ecosystem. MSP is seen as a key instrument for the Integrated Marine Policy (IMP), given the increasing competition between various maritime sectors and increasing environmental concerns. We shall consider the need to link IMP with policies of Integrated Coastal Zone Management (ICZM) to address land-sea interactions, and the need for integration across sectors and levels of governance, as well as a participatory knowledge-based approach, including increased cooperation between MSP and neighbouring third countries.

Governance change presents probably the single largest opportunity for growing food production from the sea. Researchers agree on the need to rebuild commercial stocks and on the governance challenges to achieving that. However, there are two sets of constraints. In spite of scientific advice, fishing quotas are still often higher than those recommended and the fishing industry still catches above those quotas. We outline options for encouraging sustainable fisheries, from reduced or suspension of subsidies to positive incentives and rewards for 'good behaviour'.

Governance of the oceans obviously requires a multi-level approach. Effective governance must address local activities but must also involve regional and, in many cases, even global governance. In addition, various other issues need to be addressed, such as environmental issues (marine pollution, ocean acidification), global economic developments and behavioural changes. Also, governance needs to be careful in addressing various social and political issues, for example, the different interests of in-shore versus deep-sea fishing, or of 'artisan' versus industrial fishing. Governance changes are required to rebuild commercial stocks in order to raise global food production. The cost of such changes can be paid back from increased future profits and re-directing existing subsidies.

4.3.1 Governance of the seafood sector

Towards participatory governance that involves stakeholders in planning

Social science research suggests that technological developments, economic policies and legal reform alone cannot bring the breakthroughs that many wish to see in Europe in this sector. There is broad agreement in the literature that marine governance will succeed only through adequate mechanisms for better involvement of relevant stakeholders in planning decisions.

There are a multitude of methods and tools for involving the public. Among others, such involvement might also require changing the mindset of traditional seafood experts. Co-management (Jentoft, 1989; McCay & Jentoft, 1996), or adaptive co-management (Plummer et al., 2012), has been suggested as an effective governance approach for fisheries and aquaculture since the late 1980s to boost the legitimacy of decision-making, blend scientific and local knowledge and thus arrive at more appropriate and effective governance measures. However, despite the widespread acceptance of co-management in the European Union and its conformity with principles of democracy and human rights, co-management in fisheries is also seen as bringing various important dilemmas. Three dilemmas stand out:

- 1 The representation of different stakeholders and the prioritising of certain stakeholders over others (such as on the basis of historical rights, or economic or political clout);
- 2 The unsatisfactory outcomes of some stakeholder participation processes; and
- 3 The difficulties of integrating stakeholder processes into larger, multi-level governance engagements.

The regionalisation of marine governance is considered by some a sensible future direction to address some of these problems (Soma, van Tatenhove, & van Leeuwen, 2015), as is the expansion and elaboration of marine spatial planning (Jay, 2010; Jentoft & Knol, 2014). The latter may be a useful tool for harmonising various users and uses of the ocean, including food production.

There are myriad approaches to designing participatory governance schemes. For instance, the Engage2020 project (Engage2020, n.d.) has made a worldwide scan of

methods for engagement in research, innovation and technology-related processes. It ended up with nearly 60 main methods with a large number of variants under each of them, which were included in an online methods selection tool (Engage2020, 2015) that helps users to find the most relevant methods for a given situation and for different demands. The existing methods cover the whole spectrum of functions needed for consultation, advice and governance support, as sketched in the table below.

		The role of open governance activities		
		<i>Raising knowledge</i>	<i>Forming attitudes / opinions</i>	<i>Initialising action</i>
The object of open governance activities	<i>The issue as such</i>	Assessment of options and challenges	Agenda setting	Reorientation
	<i>Societal aspects</i>	Social mapping	Mediation	New decision-making processes
	<i>Policy aspects</i>	Policy analysis	Re-structuring the policy debate	Decision-making

Table 5. (Hennen, L. et al., 2004). Functions of open governance.

Table 5 reflects all phases or types of impacts of policy advisory processes. For example, mediation refers to the roles of building bridges among actors, of breaking down mental barriers for change, or of initiating self-reflection among the actors, which often are necessary functions for creating an atmosphere of readiness for compromise or trust. Ideally, the engagement process should work itself from the upper-left corner (getting comprehensive knowledge in the topic at hand) and towards the lower-right corner (negotiation and decision-making), thereby establishing knowledge, which makes up a base for sincere attitude formation, societal mediation and debate on the policy options. Having the informed attitudes in place then makes up the bedrock underneath robust action.

The term 'multi-actor engagement' is also often used to include the wider society in governance. The term is not clearly defined. In practice, it often refers to the rather restricted inclusion of organised stakeholders (NGO's, industry, unions, etc.) in processes still dominated by scientists. However, the concept is increasingly being used to cover the interaction between science, stakeholders, policymakers and – importantly – representatives of the public (lay persons, consumers, end-users, employees etc.) in governance processes.

Wide societal engagement in the governance of complex and controversial issues brings along a series of important effects. It ensures that the knowledge base for discourse and decisions includes other forms of knowledge than the formal scientific. It provides a window for understanding the rationales behind public opinion, and the differences between informed and uninformed opinion. It sends early warnings

about potential future conflicts, making it possible to act proactively, for example, by choosing the most acceptable policy options. However, it also sends signals about uncontroversial decisions, thereby clearing the road for action, which could have been hindered by assumptions about public opinion. Further, it creates wider ownership of the decisions, which is of special importance when issues are complex and no easy solutions can be found. It is an important means of decision support in cases of uncertainty.

In summary, we conclude that when it comes to very complex processes which include high scientific uncertainty, strong and conflicting stakeholder positions and controversies about the right paths for the future (such as marine food production), the inclusion of citizens as assessors and advisors provides an important perspective, increases the democratic quality in governance and advisory processes, and helps balance potential biases among stakeholders and the scientific communities.

4.3.2 What are the implications of new technologies, new species and multi-use of ocean space for governance?

The many different uses of ocean space and new technologies, as well as the need to harness the potential of new species, are high on the political agenda of Blue Growth. However, 'ocean newcomers', such as offshore windfarms, often require vast space and generate user conflicts with competing users such as the fishing industry. This conflict has encouraged research on the prospects of integrating maritime activities under a combined management scheme that overcomes current exclusive legal rights, e.g. in the case of windfarms, fisheries and mariculture.

As we stated above, integrating marine offshore mariculture with designated windfarm areas might provide opportunities to combine two industries in the frame of a multiple-use concept (Buck et al., 2008; Griffin, Buck & Krause, 2015). The increasing limitation of favourable coastal sites for the development of modern mariculture, which is evident in various countries such as Germany, the Netherlands and Belgium, has spurred this move offshore (Buck & Krause, 2012). However, this potential must be balanced by the fact that windfarms are about the only effective 'no-take zones' in Europe. These no-take zones with new hard substrate are likely to have beneficial impacts on many commercial, as well as threatened species. Any offshore mariculture must make a point that its environmental impact can be justified, compared to the benefits of a no-take zone in the same place. In addition, stakeholder analysis (such as in Krause, Griffin, & Buck, 2011; Michler-Cieluch, Krause, & Buck, 2009; Wever, Krause, & Buck, 2015) revealed that there are different types of actors involved in the offshore realm, in contrast to the nearshore areas.

By and large, nearshore areas in Europe have a long history of traditional uses through heterogeneous stakeholder groups, from local to national levels (e.g. local fisheries communities, tourism industry, port developers, military, etc.), in which traditional user patterns emerged over a long timeframe. In contrast, offshore areas have only recently experienced conflict. This can be attributed to the relatively recent

technological advancements in shipping and platform technology, both of which have been driven by capital-strong stakeholders that operate internationally. While there is a well-established organisational structure among the stakeholders in the nearshore areas in terms of social capital and trust, as well as tested modes of conduct and social networks, these are lacking in offshore areas. These fundamental differences between nearshore and offshore waters make a streamlined 'one model' approach to multiple-use management very difficult (Krause et al., 2011).

Despite these social difficulties, solutions for combining sustainable uses of the same ocean space have seen increasing interest within the research community in Europe over the past years. Current research seems to suggest (i.e. Wever et al., 2015) that the overall acceptance of a multi-use scenario in society is high whilst opportunities and constraints, as perceived by the different stakeholder groups, vary. Framework requirements for initiating and effectively pursuing cross-sectoral offshore operation and organisation are still in need of address (Krause & Stead, 2017). These relate to creating space for participatory scenario-building and forecasting, so that policy, private industries and civil societies all have a say in shaping their future marine engagement.

In more practical terms, more attention must be given to questions of equity – who will benefit from offshore developments, who will lose and what will remain as a benefit to coastal communities? In the case of advancing offshore multi-use in a spatially efficient way, certain preconditions need to be fulfilled and streamlined to reduce the risk for offshore entrepreneurs. For example, there is a need to clarify the working tasks and siting of marine installations but also the overall regulatory conditions (e.g. determination of working rules) and allocation of responsibilities, as well as commercial arrangements or actuarial regulations and questions of ownership and liability in the exclusive economic zone (EEZ).

Future increased wild or farmed ocean production will require both scientific innovation, public consultation, and new or improved regulations. It is noteworthy that many new use systems and technologies are under way. Some appear promising, for example the previously-mentioned IMTA systems (Integrated Multi-Trophic Aquaculture systems; see also IDREEM, 2014), where the increased farming of nutrient bio-extraction organisms, such as shellfish and seaweed, may compensate for the nutrient overload in coastal waters through intensive agriculture. However, stakeholder and market acceptance is not necessarily straightforward and is based on a mix of various factors that are different between countries and regions (Alexander et al. 2016). Similar considerations may apply to the further development of closed land-based production systems (RAS) that in principle are particularly attractive for coastal areas with already-existing coastal pollution. None of these innovative production systems seem feasible in practice, without a broad societal dialogue on local, regional and national levels. Conflicts with other users of coastal areas are a likely but not necessarily an insurmountable problem, given sufficient consultation. In terms of policy implications, the literature is uniform in stressing that upstream broad societal engagement and anchoring in local identities for all these possible developments is not a luxury 'add-on', but an essential requirement for long-term success.

4.3.3. Hard choices involved in increasing ocean food production

In this section, we attempt to sketch some of the wider dilemmas involved in increasing food production. The starting point is that oceans mean many things to many people. The Millennium Ecosystem Assessment (MEA, 2005) sketches a variety of services provided by oceanic ecosystems, with food provision being only one. Clearly, prioritising food production (be it by catch or culture) may impact on other societal uses, including those highlighted in the EC's Blue Growth strategy (energy, marine biotechnology, tourism, etc.), as well as ecosystem regulatory services such as sediment capture and stabilisation in saltmarshes and mangrove forests (see Table 7 in Annex 1). Likewise, a prioritising of other uses may reduce the oceans' food production capacities.

For instance, establishing marine reserves where certain forms of fishing such as set netting and trawling are not permitted, or no-take marine reserves where all forms of extractive use are prohibited, will decrease access to fish stocks. Similarly, seabed oil pipelines and designated lanes for electricity and communications cables may all displace fishing activities. However, these fishing exclusion zones may sometimes benefit fish populations, by creating areas where they can rebuild in numbers, biomass, size and age structure, free from the regular disturbance of fishing. This may benefit adjacent fisheries, through spillover of individuals from the protected area, depending on the size of the exclusion zone in relation to the propensity for movement of specific fish species (Edgar et al., 2014). Spillover and increased local catch rates are maximised when the instantaneous emigration rate is about 0.25 (McClanahan & Mangi, 2000; Gerber et al., 2003). Thus, the size of the protected zone needs to be carefully considered if dual benefits of population rebuilding and spillover of specific species are desired. Setting aside recreational fishing reserves, where commercial fishing is prohibited, typically does not lead to rebuilding of fish stocks unless recreational fishing levels are strictly controlled (Di Franco, Bussotti, Navone, Panzalis, & Guidetti, 2009). Destructive uses of the marine environment, such as reclamation and some forms of seabed mining that cause permanent loss of seafloor habitat, are likely to cause net losses to food production as well as most other societal uses (MacDiarmid et al., 2011). Taking into account the market value of different ecosystem services (Lynch, Harcourt, Edgar, & Barrett, 2013) provides a way of offering insight into the true gains and losses involved in trade-offs.

Within capture fisheries, the choice for economic efficiency or livelihoods creates dilemmas. Small-scale fisheries are recognised as providing very significant employment opportunities for global populations, such as in the South that still have few professional alternatives (FAO, 2016b; HLPE, 2014). Fisheries-dependent regions in Europe are similarly important job creators and provide externalities, such as attractive communities for the tourism industry. However, small-scale fishing often suffers from the rationalising of fishing operations necessary for efficient monitoring and management of the fishing effort. Fishing communities are in decline and this results in a loss of ways of life that may be seen as culturally as well as economically important (Urquhart, Acott, Symes, & Zhao, 2014). The challenge is therefore to find ways to boost ocean food production, by building upon rather than subverting existing

expertise, manpower and community structure. As most of the available biomass that can be used for food production is concentrated in coastal areas within reach of existing fishing populations, labour-intensive forms of harvesting are possible. This has been termed 'technological subsidiarity' (Bavinck & Jentoft 2011). A policy choice of this kind would, however, go against the current trend of economic concentration and inequality in the fisheries.

4.3.4 What role could subsidies schemes and tailored taxation play?

It is natural to consider monetary incentives as a way to achieve policy objectives with regard to food from the ocean. For decades, subsidies and sometimes tax schemes have been supporting marine food production. There is now a wide consensus among fisheries scientists and resource economists that some past approaches to subsidising fishing and development of fishing capacity had detrimental consequences. Subsidies have intensified the overfishing problem and generated an inertia that has hampered a transition towards more sustainable fisheries. Subsidies that decrease the amount of food from the ocean by incentivising on-going overfishing include tax exemptions for fuel in fisheries and subsidies to construct, but also to de-commission fishing vessels (Clark, Munro, & Sumaila, 2005; Sumaila, Teh, Watson, Tyedmers, & Pauly, 2008; Sumaila, Lam, Le Manach, Swartz, & Pauly, 2016; Borrello, Motova, & Dentes de Carvalho, 2013).

According to Sumaila, Lam, Le Manach, Swartz, & Pauly (2013), Europe is the second largest subsidiser region after Asia, accounting for 25% of the total \$35 billion in subsidies. Fuel-tax concessions (mainly for diesel) make up the main part of subsidies. However, a recent report by the OECD raised concern about the data underlying global estimates (OECD, 2017). While the exact figures are subject to debate and contested by some fisheries economists, there is no doubt that subsidies are substantial and detrimental to fisheries sustainability. Thus, direct subsidies for marine food production should be used with caution, as they can have a detrimental indirect effect. In particular, they can easily set incentives to over-use the natural environment and thus decrease – rather than increase – the productivity of natural ecosystems. Today, there is a broad consensus among scientists that subsidies for wild capture fisheries should be abandoned completely.

In July 2016, an initiative led by the United Nations Conference on Trade and Development (UNCTAD), FAO, and the United Nations Environment Programme (UN Environment) was launched. The initiative, known as 'the road map', calls for ending harmful fishing subsidies and delivering on trade-related targets under SDG 14. UNCTAD, FAO and UN Environment are discussing the implementation of the road map.

On the other hand, tailored taxation, meaning a tax (or fee) on fish catches could be an appropriate instrument to increase the efficiency and yields of fisheries (Weitzman, 2002), in particular, if it is appropriately delineated according to the structure of fish populations (Quaas et al., 2013). The reason is that a tax on fish catches sets the incentives to reduce fishing effort to more efficient levels that sustain the productivity of fish populations.

Taxes may be an appropriate regulation instrument when they are applied to increase the private costs of actions that harm the marine environment – such as over-exploitation of marine resources, but also marine pollution. Taxing the use of nutrients that eventually end up in marine environments may help keep the oceans in a productive state with respect to food resources.

For activities that benefit the natural environment, remuneration payments may also be appropriate. Specifically, it makes economic sense to remunerate (not subsidise) the water purification service of farming filter feeders. There may be a case to subsidise research and technology development in the various sectors of marine food production.

4.3.5 Is the current multi-level greening policy of the EU for agriculture systems a tool for regional marine resource governance?

Since the early 1990s, there has been an increasing interest in the multifunctional aspects of agriculture, and attitudes towards the rural landscape and its conservation have changed. In addition to providing food and other raw materials and maintaining economic activity in rural areas, farming is now understood to have other environmental, aesthetic and social functions. While food security was the dominant concern for consumers at the onset of the EU Common Agricultural Policy (CAP), concerns relating to the environment are becoming increasingly important for citizens of the EU (Nijnik, Zahvoyska, Nijnik, & Ode, 2009).

Under the Mid-Term Review of the CAP in 2003, the EU upgraded the status of non-agricultural objectives from 'optional extra' to 'intrinsic component', and presented a broad range of multifunctional elements as key ingredients for the future direction of agricultural policy. Furthermore, the European institutions extended the list of objectives of the CAP outlined in the Treaty of Rome, to stress the need for the preservation of rural public goods (Bureau & Mahé, 2008). More recently, the concept of 'greening' that was brought in under the 2013 CAP reform, makes the direct payments system more environment-friendly. In recognition of the fact that agricultural market prices do not reflect the effort involved in providing public goods, greening supports action to adopt and maintain farming practices that help meet climate and other environmental goals. Farmers receive an area-based payment, conditional on them undertaking actions annually related to diversifying crops, maintaining permanent grassland and dedicating 5% of arable land to 'ecologically beneficial elements' (Ecological Focus Areas).

While environmental service payments are now commonplace in agriculture, the same cannot be said for marine harvesting activities. There have been conservation-style subsidies aimed at ensuring the sustainability of the resource and improved fisheries management, but the general consensus has been that all types of subsidies to the fishing industry have played a significant role in the depletion of fish stocks (von Moltke, 2011). In a generally open-access resource such as fisheries, subsidies will work to reduce costs, which results in increased effort and further pressure on the marine resource. Even when set up as a conservation measure to support the

sustainability of the resource by reducing overcapacity subsidies for vessel buy-back or buy-out of effort in a fishery, the result is payments often being re-invested in even better vessels in other fisheries, or re-entering the same fishery in other jurisdictions, or effort being increased in the remaining fleet.

As Asche (2012) points out, even when there are good socio-economic and conservation reasons for providing subsidies, the long-run results tend to be negative. Indeed, Asche calls for the abolishment of subsidies to fisheries given that they are, in his opinion, used to mitigate the effect of poor management and to delay necessary actions. We would argue that greening payments could play a limited role in promoting sustainable fishing in terms of the implementation of the discard ban. Subsidies that would facilitate the purchase of new gear that allows for the better separation of target species from other species that are not targeted but that have high survivability rates could be beneficial, as long as the gear that is supposed to be replaced is also permanently removed at the same time.

In terms of mariculture, some form of green payment system could be developed. Similar to the greening of the CAP, this would act as compensation for the additional environmental benefits that are produced as a result of improved but more expensive marine farming approaches. Similar to wild fishing, subsidies and grants have been employed for decades to compensate for the high level of risk in the start-up of aquaculture farms, again with the aim of overall production growth. Reorienting these payments toward green payments for innovation in reducing waste from the production process, and compensating producers for using more expensive feed with fewer marine resources in its composition, could be an objective. Alternatively, reduction in tax liabilities for those operators who move to more sustainable forms of mariculture is an option that could also be explored, rather than green payments.

4.4 OPPORTUNITIES FOR THE RESTORATION AND ENHANCEMENT OF COASTAL MARINE ECOSYSTEMS

Coastal ecosystems are typically highly productive, with a mosaic of different habitats and diverse biotas that yield a wide range of ecosystem-provisioning services, regulatory services and non-consumptive or social services (Costanza et al., 1997; Murillas-Maza, Virto, Gallastegui, González, & Fernández-Macho, 2011; MacDiarmid, Law, Pinkerton, & Zeldis, 2013). The complexity of emerging forms of aquaculture are currently poorly reported in the literature. Current coastal aquaculture ranges from super-intensive systems largely recirculating water, to extensive systems with no significant feed inputs that are complex polycultures, producing both food for export and local consumption. However, human effects on the marine environment are most intense in coastal localities with a long history of reclamation; coastal engineering; terrigenous sedimentation; eutrophication; pollution; invasive species introductions; fishing and gathering; vessel traffic noise and disturbance generally. These, combined with the modern impacts of climate change, sea-level rise and ocean acidification have led to habitat loss and modification, biodiversity loss and the simplification of food webs (MEA, 2005; Halpern et al., 2008; MacDiarmid et al., 2012). This has

affected the capacity of coastal marine ecosystems to produce 'safe' wild fisheries and aquaculture products (Morrison, Lowe, Parsons, Usmar, & McLeod, 2009; FAO, 2016b) and has diminished the capacity of these ecosystems to support a host of other ecosystem regulatory and social services (MEA, 2005; MacDiarmid et al., 2013). As this diminished ecosystem capacity may have occurred decades or centuries ago, it is not always obvious to modern observers and is often overlooked. Pauly has called this 'shifting baseline syndrome' (Pauly, 1995; Dayton, Tegner, Edwards, & Riser, 1998; Hughes, Bellwood, Folke, Steneck, & Wilson, 2005; Holm, Marboe, Poulsen, & MacKenzie, 2010; MacDiarmid et al., 2016). Restoration of these ecosystems offers some potential, not only to increase fisheries and aquaculture production (e.g. Bell et al., 2005), but also enhance these areas for other ecosystem services.

For example, several types of commercial fish species have juvenile phases that spend part of their time in coastal mangrove forests; seagrass beds; algal stands; or beds of large bivalves or other invertebrates (Sheaves, Baker, Nagelkerken, & Connolly, 2015; Johnson, Jenkins, Hiddink, & Hinz, 2013; Sundblad, Bergström, Sandström, & Eklöv, 2013; Espinoza, Cappel, Heupel, Tobin, & Simpfendorfer, 2014; Evans, Wilson, Field, & Moore, 2014; Félix-Hackradt, Hackradt, Treviño-Otón, Pérez-Ruzafa, & García-Charton, 2014; Jackson, Wilding, & Attrill, 2015; Le Pape & Bonhommeau, 2015). Around the world, research is under way to quantify the effects of habitat loss on fisheries recruitment and to develop habitat restoration methods and techniques that would help boost production of affected species (Turner, Thrush, Hewitt, Cummings, & Funnell, 1999; Bell et al., 2005; Airoidi & Beck, 2007; Halpern et al., 2008; Gianni et al., 2013; Rogers, Blanchard, & Mumby, 2014; Cunha et al., 2014; Jackson et al., 2015; Baggett et al., 2015).

For example, in New Zealand a new multi-year project is under way to identify and promote actions to reduce or remove bottlenecks in the production of juvenile fish for those fully-exploited species with specific juvenile biogenic habitat associations and where these habitats have been adversely affected by marine and land-based activities (see New Zealand Ministry of Business, Innovation & Employment, 2016). These habitats include subtidal seagrass, mussel beds, polychaete worm beds and sponge gardens, all of which are under pressure off European coasts and are important for some European commercial fish species (Valavanis, 2009). Consideration should be given to restoration of these ecosystems, as this could not only increase fisheries and aquaculture production but also enhance these areas for other ecosystem services. The cost of restoration can be high, however, ranging from at least US\$80 000 to US\$1 600 000 per ha (Bayraktarov et al., 2016) and needs to be weighed against the potential gains in fisheries production and ecosystems services generally. Other initiatives, such as simply banning bottom-trawling and dredging in these habitats, may be more cost-effective.

The development of breakwaters, sea walls and other man-made structures along coastlines is increasing worldwide to sustain commercial, residential and tourist activities, as well as for protection from coastal erosion and sea-level rise (Moschella et al., 2005; Bulleri & Chapman, 2010; Linley, Wilding, Black, Hawkins, & Mangi, 2007; Dugan, Airoidi, Chapman, Walker, & Schlacher, 2011). With so much human activity in

the coastal zone with the potential to remove or disturb natural habitats, the design of new structures presents opportunities to enhance habitat provision and biological productivity, including food species. The surface of an artificial structure can provide a hard substratum suitable for the larvae and propagules of many epibiotic species to settle, mature and reproduce (Barnes & Hughes, 1999). The habitat complexity offered by many structures can provide mobile species with living space, a means of escape from predators (Hixon & Beets, 1993) and opportunity for nest building and the deposition of eggs (Moring & Nicholson, 1994). The sessile and mobile reef-dwelling flora and fauna provide a readily available food source for many marine consumers (Johnson et al., 1994). Physical factors could also be important. Structures with high vertical relief can provide shelter from strong currents. Altered water currents around underwater structures can cause flocculation of plankton, which is beneficial for suspension feeders (Bohnsack & Sutherland, 1985), as well as localised effects on salinity and water temperature as the bottom waters are pushed up with currents moving over the obstruction (Lin & Su, 1994). These cooler waters mix with the warmer waters above and this has been shown to attract gatherings of animals such as fish (Lin & Su, 1994), perhaps in response to the flocculation of plankton, resulting in increased food availability. All these factors have been shown to contribute towards the success of natural reefs in supporting biologically-diverse communities and may also apply to artificial structures (Bohnsack & Sutherland, 1985).

It is widely recognised that structural complexity influences the biological community associated with a habitat (e.g. Bohnsack & Sutherland, 1985; Todd & Turner, 1986; Barkai & Branch, 1988; Sebens, 1991; Potts & Hulbert, 1994; Guichard & Bourget, 1998; Svane & Petersen, 2001; Bradshaw, Collins, & Brand, 2003) and that the physical design of artificial structures can have major consequences at multiple trophic levels (Dafforn et al., 2015). Increased habitat complexity, especially with respect to the provision and size of refuge holes, has been shown to increase species richness, abundance and biomass of fish assemblages on artificial reefs (Hixon & Beets, 1993; Carr & Hixon 1997; Danner, Wilson, & Schlotterbeck, 1994; Gratwicke & Speight, 2005; Charbonnel, Serre, Ruitton, Harmelin, & Jensen, 2002). It is not only true of fish populations. A study on an artificial reef complex in Scotland showed that artificial reef modules made from structurally-complex blocks (concrete blocks with voids) supported a 1.6 times greater standing crop of epifaunal biomass than reef modules made from the same number of reef blocks but using blocks without voids. (Beaumont, 2006). Beaumont (2006) suggested that the productivity of a reef is likely to be related to surface area which, in turn, is driven by the complexity of the reef and the scales of complexity. However, biotic interactions should also be taken into account (Ferrario, Iveša, Jaklin, Perkol-Finkel, & Airoidi, 2016). Thus, there is considerable scope for deliberately including structural complexity in the design of new coastal structures, to enhance both ecosystem function and production of specific food species. Controls are required, however, to ensure that productive habitats are not degraded through the indiscriminate dumping of inappropriate structures (e.g., vehicle tyres, car bodies), in the name of habitat restoration.

Some changes to coastal ecosystems cannot be overcome easily, and considerations of habitat restoration need to be tempered with an appreciation of what is possible. Marine habitat loss due to reclamation could be reversed, but the large direct costs and economic loss of valued real estate on harbour margins rule this out in most circumstances (Crossland, Kremer, Lindeboom, Crossland, & Le Tissier, 2005). The deposition of vast quantities of terrigenous sediments on the seafloor in sheltered coastal locations has been accelerated by human land-use practices over decades and centuries. This mud has altered seafloor habitats, often to the detriment of some food species such as clams (Lohrer, Hewitt, & Thrush, 2006) but this legacy is unlikely to ever be undone. Similarly, chemical pollutants with long half-lives persist in the marine environment, with long-term and far-reaching effects, and there is little prospect for their recovery in the short term (Walker & Livingstone, 2013). It is not possible to quantify the contribution that coastal habitat restoration could make to increasing the production of food from the ocean, without investigations designed to determine the extent of degraded areas and the potential for restoration in Europe and elsewhere.

5. Conclusions and options for how more food and biomass can be obtained from the ocean

In the preceding sections, several options on how to provide more food and biomass from the ocean have been reviewed. From a biological viewpoint, these options group into four main categories: (1) improvements in management and increased utilisation of wastes in traditional capture fisheries, (2) fishing of new wild species that are not, or only marginally, exploited today, (3) mariculture of organisms that extract their nutrients directly from the water, and (4) mariculture of organisms that require feed.

Except for improved management and increased utilisation of wastes, increased food production, whether it takes place on land or in the ocean, will increase the human footprint in one or another way (Section 1). For this reason, a rephrasing of the original question was suggested in Section 1: *'How can more food and biomass be obtained from the oceans in a way that maximises the benefits for future generations?'* The reason for this rewording is that it will be difficult, in view of today's extensive resource and environmental footprint, to avoid some reduction in benefits from the ocean harvest for present and future generations. Viewed from such a general perspective, the options provided below might well be in line with the definition of sustainable development given in the Brundtland Report (Brundtland et al., 1987):

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Basically, there is only one way to obtain significantly more food and biomass (> 100 Mt) from the ocean and that is to harvest seafood that on average is from a lower trophic level than today. Mariculture is closest to a realisation of this because macroalgae and molluscs are at the lowest TL, but also because plants now make up a substantial fraction (up to 70%) of the feed of finfish and crustacean mariculture (Section 3.2.5). Current annual mariculture production is 56 Mt and growth rates range between 6 and 8% per year (Section 2.1), i.e. in significant contrast to the stagnation in the outcome of capture fisheries (Figure 2, Section 2.1). Mariculture is said to lag agriculture by 10,000 years, but a rapid increase in the number of domesticated marine species has been observed in the last century and the number now compares to that in agriculture (Duarte et al., 2007). This provides a large biological potential for further expansion (Section 3.2). A general strategy for the further increase in mariculture production involves increased production of low TL organisms and finding new sources for the marine lipids needed for farming of finfish and crustacean (Section 3.2.1). If these lipids, together with the terrestrial plant ingredients of the feed, are produced at TL1 and 2 in the ocean, carnivore mariculture could expand independently of capture fisheries and agriculture

(Section 3.2.6). Mariculture expansion requires the use of space in coastal waters, at least in the short run, since ocean farming is presently immature. Globally, there is nearshore space suitable for substantial mariculture expansion (Gentry et al., 2017), but the competing use of coastal waters, as well as resistance against the allocation of waters for mariculture, are important constraints in many regions.

Concerning capture fisheries, there are two important constraints on how much food and biomass can be obtained.

First, established fisheries primarily target high TL species, where the natural biological production is too low (Table 1, Section 2.4) to increase fishing pressure further without reducing future production.

Second, the protection and conservation of the sea is now much higher on the agenda than at the time when traditional fisheries were established and the MSY methodology came into use. This causes resistance against harvesting wild populations in general, but particularly against the introduction of new fisheries targeting wild species that are not or only marginally exploited today (Section 3.1.3 and 3.1.4). On the other hand, the increased focus on protection and conservation gives strong incentives to improve management (Section 3.1.1) and to increase the utilisation of wastes (Section 3.1.2), so that the established fisheries can be more sustainable and provide an increased supply of seafood.

Climate change, including global warming and the expansion of oxygen minimum zones, is likely to affect the productivity of the ocean and the outcome of fisheries (Section 3.3). An expectation of reduced production at low latitudes and increased production at high latitudes is likely to affect future distribution of the wild fishery resources in the same way. This pattern might increase, due to coral bleaching and the reduction in reefs as important habitats for fish and other species in tropical areas.

Since mariculture species can be chosen for the environmental conditions in question through breeding programmes, climate change and global warming are expected to impact less on the biological potential for mariculture production, compared to fisheries. Acidification, however, might have negative effects on the future potential for bivalve production (Section 3.3.4). Pollutants such as microplastics (Section 3.3.7) might affect food safety, particularly of filter feeders like bivalves.

Based on the evidence in Section 3, we have below indicated how much more seafood and feed can be obtained globally and summarised the main constraints and uncertainties for different options in Table 6. These estimates of production potential should not be taken too literally, but are first of all meant to illustrate that there are substantial differences associated with the different options. The numbers relating to the traditional capture fisheries indicate upper boundaries for how much more food/biomass can be obtained. The numbers for mariculture, however, are not upper bounds, but rather represent potentials that are realised within 2-3 decades, with current growth rates.

With some exceptions associated with capture fisheries, the different options are in biological terms independent of each other, i.e. the realisation of one option does not influence the biological potential of another option. The first exception is Option 4 (Redirecting reduction fisheries to direct human consumption). If this option is realised, there will be a corresponding reduction in fishmeal and fish oil, which are now used as feed ingredients in mari- and agriculture. The second exception is Option 2 (Reduce discards by more selective fishing) versus Option 3 (Utilise wastes associated with discards and processing). If one succeeds in eliminating unwanted bycatch by improved selectivity (Option 2), there will be less need for discards and hence reduced potential for utilisation of wastes associated with discards (part of Option 3). Concerning Option 5 (Harvesting wild animal species that are not, or only marginally, exploited today), extensive removals of (for example) zooplankton (including krill) and mesopelagic fishes are likely to reduce the outcome of the traditional fisheries. With a precautionary harvest of the order of 20 Mt, as indicated in Table 6 (out of a combined zooplankton and mesopelagic fish biomass much larger than 1,000 Mt, Section 3.1.1), however, an observable reduction in the traditional fisheries appears unlikely.

Option 1. Improve management of established fisheries on wild species

Improved management of the established fisheries on wild species can potentially increase the global annual catch of seafood by 20 Mt per year (Section 3.1.1). The main constraint to realising this potential is a lack of adequate assessment and management tools for a large number of exploited stocks. These need to be established, in order to increase the improvement rates that have been low in the past. The rebuilding of overfished stocks will, in many places, require reduced fishery landings for several years (Section 3.1.1).

Option 2. Reduce discards by more selective fishing

There are two ways to reduce discarded bycatch - either by development of more selective harvesting or to land and utilise them (see Option 3). More fish biomass can possibly be made available, if the current discard of around 10 Mt per year (Section 3.1.2) can be decreased by increased selectivity. This assumes that the fish not caught due to increased selectivity contribute to increased catch at a later stage. The main technical constraints today are a lack of selective and gentle fishing gears and management protocols designed to reduce unwanted bycatch by avoiding spatial and temporal overlap of targeted and non-targeted species. Consequently, unless breakthroughs in harvest technology occur, this option is likely to be associated with a slow improvement rate.

Option 3. Utilise wastes associated with discards and processing

Another option to reduce loss due to discards is to land and utilise this biomass. Together with wastes during processing and at the retail level, a total waste of more than 30 Mt per year is indicated (Section 3.1.2). Except for a fraction of the discarded bycatches i.e. consumable species, this waste is likely to be more suitable as biomass

for feed (i.e. fishmeal/oil) than for direct human consumption. The main constraints to realising this potential is suitability as food and feed, which is influenced by the capacity to store, deliver, and process this waste material.

Option 4. Redirecting reduction fisheries to direct human consumption

Parts of the landings from reduction fisheries (20 Mt) may be utilised for human consumption instead of being used for the production of fishmeal and oil (Section 3.1.5). Because fishmeal and oil is currently an essential feed ingredient for finfish and shrimp mariculture, which is currently 12 Mt, this option will cause a reduced production of these species, unless fish oil can be extracted elsewhere (for example, from low TL organisms in mariculture). The net gain is further complicated by the fact that pelleted mariculture feed now depends, by weight, mainly on terrestrial feed ingredients. A food gain potential of 15 Mt is indicated in Table 4. The last 20 years has seen a redirection of reduction fisheries to direct human consumption of about 10 Mt (Figure 2, Section 2.1). If this redirection rate is to continue, it will take 40 years to realise the potential, but this will obviously depend on the market price of fishmeal/oil versus direct consumption.

Option 5. Harvesting wild animal species that are not, or marginally, exploited today

Due to the much higher natural production at lower trophic levels (Table 1 in Section 2.4), there is a large potential (>100 Mt) for capture fisheries at low TL's. Most of the TL2/TL3 production in the ocean is by zooplankton (e.g. krill) and mesopelagic fishes, which are largely unexploited but also unexplored in a resource context. Lack of adequate harvesting methodology and biological knowledge needed for management of these resources represent the main constraints. Furthermore, there are concerns that the setting up of low TL fisheries impacts on the production of established capture fisheries, as well as representing a risk for other ecosystem services (Section 3.1.3). Consequently, in the short term strongly internationally-regulated precautionary fisheries management approaches, similar to that employed for Antarctic krill, seems necessary to extract these resources. As today's annual catch of Antarctic krill (0.3 Mt) is much smaller than the catch limit (8.6 Mt) set for the Southern Ocean (Section 3.1.3), there is a potential for a high growth rate (in %) in the coming years. A precautionary potential of 20 Mt, which is expected not to decrease the output from traditional fisheries, is indicated for krill and mesopelagic fishes in Table 6.

Option 6. Harvesting wild macroalgae

There is likely a potential for harvesting more naturally-occurring macroalgae than the current 1 Mt, but removal of wild algae raises concerns associated with loss of habitat and biodiversity (Section 3.1.4). Such concerns are not expressed in the mariculture of macroalgae, which is already at a volume of 30 Mt (Figure 2 in Section 2.1), and is therefore a more likely option for harvesting large quantities of macroalgae (see Option 7).

Option 7. Mariculture of macroalgae

Macroalgae (TL1) grows on sunlight and inorganic nutrients that are naturally-occurring in the seawater. In contrast to naturally-occurring macroalgae, which are bottom-attached, cultivated macroalgae attach to manmade substrates in the free water masses (Section 3.2.3). Such habitat expansion dramatically increases the biological production potential (> 100 Mt). Important constraints for a realisation of this potential are the lack of efficient harvesting and processing technology, competition for space in coastal areas, water quality in increasingly populated coastal areas, nutritional issues and concerns for the spread of non-native species. Realisation of an additional production of 100 Mt per year (current production is 30 Mt, Figure 2 Section 2.1) would require 23 years, with an annual growth rate of 6.5%.

Option 8. Mariculture of marine herbivores such as bivalves and other filter feeders

Like macroalgae, bivalves and other filter feeders feed on nutrients (phytoplankton and other particulate organic material) that are naturally-occurring in the seawater. These are commonly classified as herbivores (TL2) although this is not strictly true. Placing filtering organisms (e.g. mussels), which by nature are bottom-attached, in the free water masses with suitable currents enables a high production per unit area (Section 3.2.4). As for macroalgae, the biological potential for providing more food and biomass is large (> 100 Mt). Realisation of an additional production of 100 Mt per year (current production is 16 Mt, Figure 2 Section 2.1) would require 32 years, with an annual growth rate of 6.5%. Unlike macroalgae, bivalves (like mussels, scallops and oysters) are well-established food in most parts of the world. There are several constraints to realising the biological potential, such as competition for space and insufficient water quality in coastal areas, lack of technology for open-ocean farming, and concerns for interaction with wild stocks. Co-location of algal farms with shellfish farms has been suggested to alleviate risks of ocean acidification impacts on shellfish, but these groups are indirect competitors for the same resources, light and inorganic nutrients, as shellfish feed on phytoplankton.

Option 9. Mariculture of marine carnivores

Carnivore species of high TL represent attractive and valued seafood. The severe biological constraint for capturing more such wild species (Section 2.4) will likely increase the demand for cultivated carnivores. Fish oils are a crucial feed ingredient for the group and new sources are needed for the expansion of carnivore aquaculture (Sections 3.2.5, 3.2.6 and 3.2.7). One potential fish oil source is the increased utilisation of wastes associated with discards and processing in fisheries (Option 3, above). Important to note is that the essential fatty acids of 'fish oils' (n-3 rich lipids) are produced at the bottom of the food chain (phytoplankton) and therefore available in other species than those targeted in the reduction fisheries. Other sources (Section 3.2.6) are therefore harvested zooplankton and mesopelagic fish (Option 5), cultured macroalgae and microorganisms like thraustochytrids and suitable marine microalgae, (Option 7) and other suitable filter feeders that can be cultured (Option

8). The potential n-3 lipid rich sources from e.g. wastes in capture fisheries indicated in Table 6 could provide an increase in carnivore mariculture of more than 10 Mt. This is roughly a doubling of the current global volume, which will take less than ten years with the current annual growth in fish and shrimp production (7-8% per year, Section 2.1). If new n-3 rich lipids, together with the terrestrial plant ingredients used in feed today, are replaced by mariculture production (e.g., macroalgae, single cell biomass and cultured filter feeders), there will be no direct link and constraint on mariculture by resources from capture fisheries and agriculture, and the potential will be much higher than indicated in Table 6.

Additional to fish oil availability, competition for space in coastal areas, environmental concerns related to the release of organic matter and pharmaceutical substances, and concerns for interaction with wild stocks (genetically and by diseases) are important constraints for the expansion of carnivore mariculture in many locations.

Option 10. Integrated multi-trophic aquaculture (IMTA)

IMTA is primarily a production method that potentially can counteract some of the constraints that apply to the biological potentials for obtaining more carnivores, bivalves and macroalgae (Section 3.2.8). The potential benefits are primarily the reduced environmental impacts of carnivore mariculture, added value of production, and reduced competition for space.

Environmental footprint and uncertainties associated with increased food production

As already noted, the environmental footprint associated with increased food production differs for the different options addressed above. The options aiming at the improvement of existing activities will not cause a larger human footprint than is already seen, unless more energy or other resource input is required. Improved management (Option 1), reduced discards (Options 2 and 3) and redirection of reduction fisheries to human food (Option 4) all have this advantage. On the other hand, the expansion of mariculture (Options 4-10) is associated with an increased footprint. The spread of non-native species and diseases, the release of nutrients and pharmaceutical substances, and the occupation of space are important elements in such a footprint (Section 3.2). An increased environmental footprint represents an important constraint for obtaining more food and biomass from the ocean. Table 6 summarises the main constraints, as well as the uncertainties (Section 3.3) that are associated with each of the ten options for increased food production.

Options for how to obtain more food and biomass	Biological potential for obtaining more food/biomass (MMT/year)		Today's biological and technical constraints for realisation of the biological potential (Section 3.1)	Uncertainties that might affect the future biological potential (Section 3.3)
	Food	Biomass (that can serve as feed)		
Improve management of established fisheries on wild species (Section 3.1.1)	20		Lack of adequate assessment tools for most stocks Rebuilding and restructuring (of size distribution) of stocks require reduced landings over initial years	Warming might decrease total fish production and is predicted to alter geographical distribution of species and their number Warming, acidification and deoxygenation might lead to habitat degradation and reduced fish production Acidification might reduce production of bivalves
Reduce discarded bycatches (Section 3.1.2)	10		Lack of selective and gentle fishing gears Lack of management systems aimed at reducing bycatches	
Increase utilisation of wastes associated with discards and processing (Section 3.1.2)		>30	Lack of capacity to store, deliver and process discards and offal Uncertain suitability as feed ingredients	
Harvest wild animal species that are marginally or not exploited today (zooplankton and mesopelagic fishes) (Section 3.1.3)	?	(>100?) 20*	*Estimate of 20 represents a precautionary approach (krill and mesopelagic) Lack of biological knowledge required for sustainable management Concerns for reduced outcome of traditional fisheries and risk of affecting other ecosystem services Lack of harvesting technology	Warming might alter location and decrease total production of zooplankton and fishes Climate change is predicted to impact primary productivity Expansion of the oxygen minimum zones might affect distribution and production of mesopelagic fishes

Options for how to obtain more food and biomass	Biological potential for obtaining more food/biomass (MMT/year)		Today's biological and technical constraints for realisation of the biological potential (Section 3.1)	Uncertainties that might affect the future biological potential (Section 3.3)
	Food	Biomass (that can serve as feed)		
Redirect reduction fisheries to direct human consumption (Section 3.1.5)	15	-20 (loss of oil/meal)	<p>Competing demand for production of fishmeal and oil</p> <p>Resistance to fish these species below MSY levels</p>	
Harvest of wild algae (Section 3.1.4)	1	1	<p>Concern for negative effects on habitat and local biodiversity</p> <p>Food safety issues concerning affinity for heavy metals and radionucleids</p> <p>Acceptability as food</p>	Several species of non-calcifying algae are predicted to benefit from high CO ₂
Mariculture of algae (Section 3.2.3)	>50?	>50	<p>Concerns for spread of non-native species</p> <p>Genetic genotypes are too uniform and increases risk of diseases</p> <p>Food safety issues concerning affinity for heavy metals and radionucleids</p> <p>Lack of high-efficiency harvesting and processing technologies</p> <p>Acceptability as food</p> <p>Competition for available space for seaweed farms in coastal areas</p>	<p>Non-calcifying algae are predicted to benefit from high CO₂</p> <p>Positive effect on seawater CO₂ if grown in synergy with calcifiers impacted by ocean acidification.</p>

Options for how to obtain more food and biomass	Biological potential for obtaining more food/biomass (MMT/year)		Today's biological and technical constraints for realisation of the biological potential (Section 3.1)	Uncertainties that might affect the future biological potential (Section 3.3)
	Food	Biomass (that can serve as feed)		
Mariculture of filter feeders (e.g. molluscs) (Section 3.2.4)	>100	Potential feed source for carnivore mariculture	<p>Concerns for spread of non-native species</p> <p>Competition for space and insufficient water quality in certain coastal areas</p> <p>Dense farming may increase spread of disease</p> <p>Lack of technology/ experience from open ocean farming</p>	<p>Acidification might reduce development and growth of filter feeders with calcareous shell (bivalves)</p> <p>Uptake of microplastic might affect nutritional value</p> <p>Global warming is predicted to increase the spread of pathogens</p>
Mariculture of marine carnivores (finfish and shrimps, Section 3.2.5 and 3.2.7)	>10		<p>Availability of feed resources rich in LC n-3 fatty acids</p> <p>Competition for space in coastal areas</p> <p>Environmental concerns related to release of nutrients, organic matter and pharmaceutical substances</p> <p>Concerns for interaction with wild stocks (genetically and diseases)</p>	
Integrated multi-trophic aquaculture (IMTA, Section 3.2.8)	+	+	Might reduce the environmental footprint of fish farming, but the added economic value of IMTA is uncertain	

Table 6. Summary of options for more food from the ocean on a global scale. With some exceptions (see text), the indicated biological potentials of the different options are independent of each other. The biological potentials associated with the traditional capture fisheries indicate upper bounds, while the mariculture options indicate potentials that can be realised within 2-3 decades, assuming today's growth rates.

Market and Social Responses to New Challenges

The challenge of obtaining more food from the sea raises a number of contested issues. Researchers are in almost universal agreement that there are major benefits by improving marine management, both at the European and global scales. There is also widespread agreement around the bio-economic benefits of a right-based management system and a change of consumer preference towards food from lower trophic levels. However, the social and cultural issues connected with such a reorientation of the marine sector are many and conflicted.

The options below address the structure of the relationship between market and social responses. In terms of governance, we focus on rights-based management and accurate assessments of fishing behaviour, both at bycatch level and emerging new industries, and the importance of managing and regulating fishing and mariculture with citizen participation and contribution. Subsidies and taxation policies should be used with caution and only to stimulate sustainable development.

Addressing issues of legal frameworks versus social licence and social acceptance of new measures is crucial to understanding the feasibility of any new policy. Our research-based options below aim to underpin a democratic co-design of policies, rather than predict public responses or determine social behaviour. Education and inclusive decision-making lead to open and constructive societies that can help frame and determine a sustainable future food system.

Option 11. Rights-based management

There is wide agreement among economists that rights-based management – for example, a management approach where fishers own some type of individual fishing right that reduces the 'race to fish' – has been documented to lead to higher-quality fish, better selection for age classes and species, and smoothing out supply over time. This option would support Options 1, 2, and 3 above.

Option 12. Support for start-ups

There is consensus among the experts that the appropriate approach to facilitating start-up investments for licensed marine operations is to set up clear, transparent and harmonised regulation and rules. This is critically important for Options 6-10 above.

Option 13. Consumer information

Consumers need trustworthy information about production processes and the environmental consequences of fish farming, in order to make increased supply from aquaculture acceptable to them. Such information could help promote *SMART Eating*, by matching information to consumption. This is important for Options 4-10 above.

Option 14. Social responsibility

Decision-support tools spanning economic, socio-cultural and ethical issues should be utilised and co-developed with users as an integrated part of a revised CSR. To generate and maintain legitimacy, instruments are needed that focus on open innovation, co-production of knowledge, consensus-building and social responsibility on multiple levels.

Option 15. Citizen involvement

There is broad agreement in the literature that marine governance will succeed only through adequate mechanisms for better involvement of relevant stakeholders in planning decisions. With very complex processes involving a high scientific uncertainty, strong and conflicting stakeholder positions and controversy about the right paths for the future (as is the case with marine food production), including citizens as assessors and advisors provides an important perspective, increases the democratic quality of governance and advisory processes, and helps to address potential bias among stakeholders and the scientific communities.

Option 16. Job prioritisation

As most of the available biomass that can be used for food production is concentrated in coastal areas within reach of existing fishing populations, labour-intensive forms of harvesting are possible. This has been termed 'technological subsidiarity'. A policy choice of this kind would go against the current trend of economic concentration and inequality in fisheries.

Option 17. Financial strategies

Direct subsidies for marine food production should be used with caution, as they can have detrimental indirect effects. Taxes may be an appropriate regulation instrument when they are applied to increasing the private costs of actions that harm the marine environment. Greening payments could play a limited role in promoting sustainable fishing.

Option 18. Coastal engineering

There is considerable scope for deliberately including structural complexity in the design of new coastal and offshore engineering developments to enhance both ecosystem function and production of specific food species.



6. References

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Annex 1. Working Group Members

Professor Dag Lorents Aksnes, University of Bergen (Norway), Chair, Working Group 1 (Natural Sciences)

Professor Poul Holm, Trinity College Dublin (Ireland), Chair, Working Group 2 (Social Sciences and Humanities)

Professor Maarten Bavinck, University of Amsterdam (Netherlands)

Professor Frank Biermann, Utrecht University (Netherlands)

Professor Roberto Danovaro, Polytechnic University of Marche and Stazione Zoologica Anton Dohrn (Italy)

Professor Patricia Harvey, University of Greenwich (United Kingdom)

Dr Stephen Hynes, National University of Ireland Galway (Ireland)

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Dr Sylvie Lapègue, French Research Institute for Exploitation of the Sea, IFREMER (France)

Dr Alison MacDiarmid, National Institute of Water and Atmospheric Research (New Zealand)

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Professor Daniela Schmidt, University of Bristol (United Kingdom)

Professor Patrick Sorgeloos, Ghent University (Belgium)

Professor Michael St John, Technical University of Denmark (Denmark)



Annex 2. Background to the report

The question on Food from the Oceans was put to the Scientific Advice Mechanism (SAM) by Commissioner Vella, Commissioner for Environment, Maritime Affairs and Fisheries, behalf of the European Commission. It was taken up by the SAM High Level Group of Scientific Advisers (HLG).

Based on the resulting scoping paper (SAM, 2016), the key question asked was:

How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?

Within the SAM High-Level Group, Professor Carina Keskitalo led on this topic, in cooperation with other HLG members, Professors Elvira Fortunato and Janusz Bujnicki.

The SAPEA Consortium was asked to produce the evidence review report on the topic. The SAPEA Board approved *Academia Europaea* as the Lead Academy, working with the other SAPEA partners.

A Coordination Group was set up and met from February 2017, chaired by Professor Keskitalo. It was composed of the members of the HLG involved, Professor Ole Petersen (on behalf of SAPEA and *Academia Europaea*) and the two Working Group Chairs (see Annex 8). Appointed staff members from SAPEA and from the SAM Unit attended the meetings.

SAPEA set up two international and interdisciplinary working groups, based on a process of formal nomination by academies and assessed by a selection committee (see Annex 1). The committee followed established guidelines on ensuring fair representation on the working groups in respect of gender, geographical spread, etc., whilst adhering to the primary criterion of scientific excellence in the field. Where necessary, other experts in specific fields were invited onto the working group, provided the key criteria for selection were met. All invitees to the working groups were required to declare any conflict of interest.

Working Group 1 examined issues within the natural sciences/technology and Working Group 2 the social science/humanities. Professor Dag Lorents Aksnes, University of Bergen, chaired Working Group 1 and Professor Poul Holm, Trinity College Dublin, Working Group 2.

Both working groups held two physical meetings each, plus one joint physical meeting. All meetings took place in May and June 2017. Representatives from Working Group 1 attended all meetings of Working Group 2, to ensure synergy. The working groups revised the questions and drafted the report, as well as overseeing the literature review, conducted by Cardiff University Library Services. The SAM Unit provided references covering the grey literature.

The working groups were supported by two scientific writers.

The deadline of 15th August 2017 for submission of the final version of the first draft of the Evidence Review Report was met. This draft was scrutinised at a workshop of invited experts on 14th September 2017, hosted at the European Commission and set up to act as a bridge between the SAPEA report and the policy-based scientific opinion, written by the SAM HLG. The revised report went for peer review in October. The final version of the report was endorsed by the SAPEA Board, on behalf of its member academies.

It is planned that both the evidence review report and the scientific opinion are published at the same time, late in 2017. The intention is that they will be used in the planning of the EU's future political priorities and resource allocation. These include the preparation of the Commission's post-2020 Multi-Annual Financial Framework (MFF), the successor to the European Maritime and Fisheries Fund, and a range of other policy areas such as the implementation of the *Blue Growth Strategy, Agenda 2030*, ocean governance and development cooperation.



Annex 3. Literature search strategy statement

The literature review was conducted based on the rapid review method, which takes a rigorous but streamlined approach to synthesising evidence. Information professionals, who are also subject specialists, supported each of the working groups. A separate search was conducted for grey literature (for example, conference reports and technical papers). All results were stored in a shared repository, created using reference management software, Mendeley.

Working Group 1

The rapid review search strategies were undertaken by:

- Nigel Morgan – Subject Librarian, Cardiff University Library Service
- Delyth Morris – Subject Librarian & systematic review specialist, Cardiff University Library Service

Date of searches: May 2017

Limits applied: Review only, 2000-present, English language only

Searches: (listed opposite)

Chapter 2: how can more food and biomass be obtained by sustainable harvesting of wild populations?

Database	No. of results	Date
BIOSIS Citation Index	1008	2000-Dec 2016
Web of Science	1188	2000-17/05/2017
Scopus	414	2000-17/05/2017

Total after de-duplicating: **1904**

Final number of results: **345**

Search strategy

- 1 (Food* SAME (ocean* OR sea* OR marine*))
- 2 (biomass* SAME (ocean* OR sea* OR marine*))
- 3 (biofuel* SAME (ocean* OR sea* OR marine*))
- 4 ("organic matter" NEAR fuel*)
- 5 (invertebra* SAME (sea* OR ocean* OR marine*))
- 6 (mollusc* SAME (sea* OR ocean* OR marine*))
- 7 (fish* OR seafood* OR algae OR microalgae OR krill* OR plankton* OR seaweed* OR microplankton* OR crustacean* OR echinoderm* OR zooplankton* OR mesopelagic OR macroalgae OR macrophyte*)
- 8 Or/1-7
- 9 ((harvest* OR fish* OR discard*) SAME (sustain* OR replenish* OR supportab* OR renewab* OR viab*))
- 10 8 AND 9
- 11 Limit 10 to English language
- 12 Limit 11 to literature review
- 13 Limit 12 to 2000-current

The above search was undertaken in BIOSIS and replicated as closely as possible in the other databases.

Chapter 3: how can more food and biomass be obtained by sustainable mariculture?

Database	No. of results	Date
BIOSIS Citation Index	462	2000-Dec 2016
Web of Science	334	2000-18/05/2017
Scopus	96	2000-18/05/2017

Total after de-duplicating: **628**

Final number of results: **261**

Search strategy

- 1 (Food* SAME (ocean* OR sea* OR marine*))
- 2 (biomass* SAME (ocean* OR sea* OR marine*))
- 3 (biofuel* SAME (ocean* OR sea* OR marine*))
- 4 ("organic matter" NEAR fuel*)
- 5 (invertebra* SAME (sea* OR ocean* OR marine*))
- 6 (mollusc* SAME (sea* OR ocean* OR marine*))
- 7 (fish* OR seafood* OR algae OR microalgae OR krill* OR plankton* OR seaweed* OR microplankton* OR crustacean* OR echinoderm* OR zooplankton* OR mesopelagic OR macroalgae OR macrophyte*)
- 8 Or/1-7
- 9 ((sustain* OR replenish* OR supportab* OR renewab* OR viab*) SAME (mariculture* OR aquaculture*))
- 10 (cultivat* SAME (finfish OR shrimp* OR "filter feeder*" OR "forage fish*" OR bivalve* OR tunicate* OR "marine plant*" OR seaweed* OR phytoplankton*))
- 11 9 OR 10
- 12 8 AND 11
- 13 Limit 12 to English language
- 14 Limit 13 to literature review
- 15 Limit 14 to 2000-current

The above search was undertaken in BIOSIS and replicated as closely as possible in the other databases.

Chapter 4: Uncertainties – climate change

Database	No. of results	Date
BIOSIS Citation Index	334	2000-Dec 2016
Web of Science	363	2000-24/05/2017
Scopus	456	2000-24/05/2017

Total after de-duplicating: **876**

Final number of results: **148**

Search strategy

- 1 (Food* SAME (ocean* OR sea* OR marine*))
- 2 (biomass* SAME (ocean* OR sea* OR marine*))
- 3 (biofuel* SAME (ocean* OR sea* OR marine*))
- 4 ("organic matter" NEAR fuel*)
- 5 (invertebra* SAME (sea* OR ocean* OR marine*))
- 6 (mollusc* SAME (sea* OR ocean* OR marine*))
- 7 (fish* OR seafood* OR algae OR microalgae OR krill* OR plankton* OR seaweed* OR microplankton* OR crustacean* OR echinoderm* OR zooplankton* OR mesopelagic OR macroalgae OR macrophyte*)
- 8 Or/1-7
- 9 ((sustain* OR replenish* OR supportab* OR renewab* OR viab*))
- 10 ("climat* change*" OR "global warming" OR "ocean acidification" OR "ocean warming" OR "el nino" OR "oxygen deplet*" OR pollut*)
- 11 8 AND 9 AND 10
- 12 Limit 11 to English language
- 13 Limit 12 to literature review
- 14 Limit 13 to 2000-current

The above search was undertaken in BIOSIS and replicated as closely as possible in the other databases.

Chapter 4: Food safety

Database	No. of results	Date
BIOSIS Citation Index	284	2000-Dec 2016
Web of Science	302	2000-24/05/2017
Scopus	307	2000-24/05/2017

Total after de-duplicating: **876**

Final number of results: **148**

Search strategy

- 1 (Food* SAME (ocean* OR sea* OR marine*))
- 2 (biomass* SAME (ocean* OR sea* OR marine*))
- 3 (biofuel* SAME (ocean* OR sea* OR marine*))
- 4 ("organic matter" NEAR fuel*)
- 5 (invertebra* SAME (sea* OR ocean* OR marine*))
- 6 (mollusc* SAME (sea* OR ocean* OR marine*))
- 7 (fish* OR seafood* OR algae OR microalgae OR krill* OR plankton* OR seaweed* OR microplankton* OR crustacean* OR echinoderm* OR zooplankton* OR mesopelagic OR macroalgae OR macrophyte*)
- 8 Or/1-7
- 9 ((sustain* OR replenish* OR supportab* OR renewab* OR viab*)
- 10 (nutrition* OR diet* OR "food safety")
- 11 8 AND 9 AND 10
- 12 Limit 11 to English language
- 13 Limit 12 to literature review
- 14 Limit 13 to 2000-current

The above search was undertaken in BIOSIS and replicated as closely as possible in the other databases.

Working Group 2

The rapid review search strategies were undertaken by:

- Sarah Puzey – Subject Librarian, Cardiff University Library Service

Date of searches: June 2017

Limits applied: title/abstract searches only, restrict using database subject filters, 2000-present, English language only

Searches:

What future trajectories of production are possible?		
Database	No. of results	Date
Scopus (reviews only)	31	2000-07/06/2017
Web of Science (reviews only)	63	2000-07/06/2017
Scopus (articles)	220	2000-08/06/2017
Web of Science (articles)	286	2000-08/06/2017
Total after de-duplicating: 550		
Final number of results: 143		
Search strategy		
1 (food OR biomass)		
2 (marine OR fish* OR ocean OR coast* OR aquatic OR sea)		
3 (produc* OR harvest* OR wild OR farmed OR process* OR fish* OR aquaculture OR aquafarming OR yield)		
4 (trajector* OR future OR anticipate OR forecast OR estimate OR prospect OR current OR outlook OR potential OR opportunit*)		
5 1 AND 2 AND 3 AND 4		
The above search was undertaken in Scopus and replicated as closely as possible in the other databases.		

What are the consequences/opportunities for coastal and other populations of any of these types of food production extension?

Database	No. of results	Date
Scopus (search 1. reviews)	12	2000-07/06/2017
Scopus (search 2. reviews)	35	2000-07/06/2017
Web of Science (search 1. Reviews)	23	2000-07/06/2017
Web of Science (search 2. Reviews)	79	2000-07/06/2017
Scopus (search 1. articles)	74	2000-08/06/2017
Scopus (search 1. articles)	334	2000-08/06/2017
Web of Science (search 1. articles)	121	2000-08/06/2017
Web of Science (search 1. articles)	409	2000-09/06/2017
Total after de-duplicating: 773		
Final number of results: 221		

What are the consequences/opportunities for coastal and other populations of any of these types of food production extension?

Search strategy 1

- 1 (food OR biomass)
- 2 (marine OR fish* OR ocean OR coast* OR aquatic OR sea)
- 3 (produc* OR harvest* OR wild OR farmed OR process* OR fish* OR aquaculture OR aquafarming OR yield)
- 4 (extension OR increase OR growth OR expansion OR intensif*)
- 5 (consequence OR opportunit* OR outcome OR benefit OR disadvantage* OR advantage* OR effect OR potential OR result)
- 6 (population OR people OR social OR communit*)
- 7 1 AND 2 AND 3 AND 4 AND 5 AND 6

The above search was undertaken in Scopus and replicated as closely as possible in the other databases.

Search strategy 2

- 1 (food OR biomass)
- 2 (marine OR fish* OR ocean OR coast* OR aquatic OR sea)
- 3 (produc* OR harvest* OR wild OR farmed OR process* OR fish* OR aquaculture OR aquafarming OR yield)
- 4 (population OR people OR social OR communit*)
- 5 1 AND 2 AND 3 AND 4

The above search was undertaken in Scopus and replicated as closely as possible in the other databases.

What governance arrangements would be required to develop and ensure sustainable harvest of increased marine production?

Database	No. of results	Date
Scopus (search 1. reviews)	4	2000-07/06/2017
Scopus (search 2. reviews)	12	2000-07/06/2017
Web of Science (search 1. Reviews)	6	2000-07/06/2017
Web of Science (search 2. Reviews)	22	2000-07/06/2017
Scopus (search 1. articles)	21	2000-08/06/2017
Scopus (search 1. articles)	56	2000-08/06/2017
Web of Science (search 1. articles)	44	2000-08/06/2017
Web of Science (search 1. articles)	114	2000-08/06/2017
Total after de-duplicating: 183		
Final number of results: 198		

What governance arrangements would be required to develop and ensure sustainable harvest of increased marine production?

Search strategy 1

- 1 (food OR biomass)
- 2 (marine OR fish* OR ocean OR coast* OR aquatic OR sea)
- 3 (produc* OR harvest* OR wild OR farmed OR process* OR fish* OR aquaculture OR aquafarming OR yield)
- 4 (extension OR increase OR growth OR expansion OR intensif*)
- 5 (sustainab* OR overharvesting OR conservation OR overfishing OR green OR security OR eco OR renewable OR supportab* Or viab* OR replenish*)
- 6 (governance OR law OR regulation OR legislation OR certification OR control OR code)
- 7 1 AND 2 AND 3 AND 4 AND 5 AND 6

The above search was undertaken in Scopus and replicated as closely as possible in the other databases.

Search strategy 2

- 1 (food OR biomass)
- 2 (marine OR fish* OR ocean OR coast* OR aquatic OR sea)
- 3 (sustainab* OR overharvesting OR conservation OR overfishing OR green OR security OR eco OR renewable OR supportab* Or viab* OR replenish*)
- 4 (governance OR law OR regulation OR legislation OR certification OR control OR code)
- 5 1 AND 2 AND 3 AND 4

The above search was undertaken in Scopus and replicated as closely as possible in the other databases.

Grey literature

Documents were retrieved and selected on the basis of:

- 1 Their relevance to one or other or several aspects of the question, based on trial searches using keywords and phrases in
 - Google
 - Google Scholar
 - Scopus
- 2 The recommendations of various experts in the field
 - Individual experts, stakeholder bodies (Oceana, the European Marine Board, the Norwegian Seafood Innovation Cluster, SCARFish, etc.)
 - EC staff within different Commission departments and other European bodies (RTD, JRC, MARE, EEA), with specialised knowledge
 - Relevant conference presentations and reports in the public domain



Annex 4. Table 7. Impact of increases in different forms of fishing and aquaculture on marine ecosystem services

Reference: MacDiarmid, A. B., Law, C. S., Pinkerton, M., & Zeldis, J. (2013). New Zealand marine ecosystem services. *Ecosystem services in New Zealand—Conditions and trends*, 238-253.

Key: + positive; – negative; N neutral.

Marine Ecosystem Services	Type of fishing					Type of mariculture			
	Bottom trawling / dredging	Midwater trawling	Gill/trammel netting	Longlining /trolling	Trapping	Coastal pond culture	Sea cage culture of predators	Sea cage culture of herbivores	Dropper line culture of filter feeders/algae
Regulatory services									
Climate regulation	N	N	N	N	N	-	N	N	N
Sediment capture, stabilization	-	N	-	N	N	-	-	-	+
Carbon capture & sequestration	-	N	-	N	N	-	N	N	+
Pollutant capture & sequestration	-	N	-	N	N	-	-	N	+
Pollutant detoxification	-	N	-	N	N	-	-	N	+
Storm surge amelioration	N	N	N	N	N	-	N	N	N
Erosion dampening	N	N	N	N	N	-	+	+	+
Storage of nutrients	-	N	-	N	N	-	N	N	+
Net annual oxygen production	N	N	N	N	N	-	N	N	+
Provision of biogenic habitat materials	-	N	-	N	N	-	N	N	+

Marine Ecosystem Services	Type of fishing					Type of mariculture			
	Bottom trawling / dredging	Midwater trawling	Gill/trammel netting	Longlining/trolling	Trapping	Coastal pond culture	Sea cage culture of predators	Sea cage culture of herbivores	Dropper line culture of filter feeders/algae
Provisioning services									
Wild food support and provision	-	N	-	N	N	-	-	N	+
Aquaculture support and provision	-	N	-	N	N	-	N	N	-
Presently used biological compounds (number)	N	N	N	N	N	N	N	N	+
Bacterially enhanced gas and mineral deposits	-	N	N	N	N	N	N	N	N
Biodiversity (future proofing service)	-	-	-	-	-	-	N	N	N
Non-consumptive services									
Visual amenity value (landscape/ seascape)	-	N	N	-	-	-	-	-	-
Spiritual and inspirational value	N	N	N	N	N	-	-	-	-
Existence value	-	-	-	-	-	-	-	-	-
Areas supporting coastal non-water recreation	N	N	N	N	N	-	N	N	N
Areas supporting water recreation	-	-	-	-	-	-	-	-	-
Current foci for education	N	N	N	N	N	N	N	N	N
Current focus for scientific research	+	+	+	+	+	+	+	+	+
Currently watchable wildlife	-	-	-	-	N	-	N	N	+
Biological indicators of ecosystem health	+	+	+	+	+	N	N	N	N



Annex 5. Glossary of key definitions and terms

Sources:

FAO. (n.d.). *FAO Term Portal*. Retrieved from <http://www.fao.org/faoterm/en/>

Froese, R., & Pauly, D. (Eds.). (2017). *FishBase Glossary*. Retrieved from <http://www.fishbase.org/Glossary/Glossary.php>

Abiotic stressors	Non-living factors that have a negative impact on the living organisms in a specific environment. http://www.biology-online.org/dictionary/Abiotic_stress
Alginates	Industrial product derived from brown algae (seaweeds). (FAO)
Anthropogenic	Involving the impact (usually negative) of humankind on nature. (FishBase)
Aquaculture	The farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants. Farming implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated, the planning, development and operation of aquaculture systems, sites, facilities and practices, and the production and transport. (FAO)
Aquaponics	A system of aquaculture in which the waste produced by farmed fish or other aquatic creatures supplies the nutrients for plants grown hydroponically, which in turn purify the water. https://en.oxforddictionaries.com/definition/aquaponics
Autotrophic process	The process by which an organism manufactures its own food from inorganic constituents, often through the use of energy obtained from light (photoautotrophic) or other energy sources (chemoautotrophic). (FishBase)
Benthic ecosystem	Portion of the marine realm composed of, or dominated by, the bottom substrate and its organisms. (FishBase)

Benthic fauna	The animals living and feeding on the bottom of the ocean. (FishBase)
Benthopelagic fishes	Fishes living near the bottom as well as in midwaters or near the surface, and feeding on benthic as well as free swimming organisms. (FishBase)
Biofuel	Any fuel that is derived from biomass—that is, plant material or animal waste. https://www.britannica.com/technology/biofuel
Biomass	(a) The total live weight of a group (or stock) of living organisms (e.g. fish, plankton) or of some defined fraction of it (e.g. spawners), in an area, at a particular time. (b) Any quantitative estimate of the total mass of organisms comprising all or part of a population or any other specified unit, or within a given area at a given time; measured as volume, mass (live, dead, dry or ash-free weight) or energy (joules, calories). (FAO)
By-catch	Part of a catch of a fishing unit taken incidentally in addition to the target species towards which fishing effort is directed. Some or all of it may be returned to the sea as discards, usually dead or dying. (FAO)
Capture fishery	The sum (or range) of all activities to harvest a given fish resource. It may refer to the location (e.g. Morocco, Georges Bank), the target resource (e.g. hake), the technology used (e.g. trawl or beach seine), the social characteristics (e.g. artisanal, industrial), the purpose (e.g. commercial, subsistence, or recreational) as well as the season (e.g. winter). (FAO)
Carnivores	Animals that eat herbivores or other carnivores. Their trophic level is 3 or higher (e.g. most fish species)
Cephalopods	Animals (molluscs) with tentacles converging at the head, around the mouth (examples: squids, cuttlefish, and octopus). (FAO)
Corporate Social Responsibility (CSR)	Transparent business practices that are based on ethical values, compliance with legal requirements, and respect for people, communities, and the environment. Thus, beyond making profits, companies are responsible for the totality of their impact on people and the planet. https://web.archive.org/web/20071012014240/http://www.rhcatalyst.org/site/DocServer/CSRQ_A.pdf?docID=103

Demersal	Living in close relation with the bottom and depending on it. Example: Cods, Groupers and lobsters are demersal resources. The term demersal fish usually refers to the living mode of the adult. (FAO)
Diadromous species	A species, a fish, which undertakes spawning migration from ocean to river or vice versa. (FAO)
Fishery	Generally, a fishery is an activity leading to harvesting of fish. It may involve capture of wild fish or raising of fish through aquaculture. (FAO)
Food web	The network of feeding relationships within an ecosystem or a community i.e. the predator-prey relationships. (FAO)
Genotypes	The particular combination of genes present in the cells of an individual. (FAO)
Herbivores	Animals (e.g. some zooplankton and bivalves) of trophic level 2 that eat plants (e.g. phytoplankton)
Hydrographic conditions	Physical features of the oceans, seas, lakes, rivers, and their adjoining coastal areas, with particular reference to their use for navigational purposes. (FishBase)
Hypoxia	Deficiency of oxygen; low levels of dissolved oxygen in water (~< 3 ppm) that are extremely stressful to most aquatic life. Stress applied to fish when measuring, e.g., oxygen consumption. (FishBase)
Keystone species	A species whose loss from an ecosystem would cause a greater than average change in other species populations or ecosystem processes; whose continued well-being is vital for the functioning of a whole community, such as the herring in the North Atlantic or krill in Antarctica. (FishBase)
Krill	Now commonly used as the common term for Euphausiids, a family of crustaceans found throughout the world oceans. There are 85 species of krill, some of which are exploited commercially. The Antarctic Krill is <i>Euphausia superba</i> . Other species include <i>Euphausia pacifica</i> , <i>Euphausia nana</i> , <i>Thysanoessa inermis</i> , <i>meganyctiphanes norvegica</i> , <i>Nyctiphanes australis</i> . (FAO)

Landing	Weight of what is landed at a landing site. May be different from the catch (which includes the discards). (FAO)
Length at first capture	Length at which 50% of the animals sampled are retained by the gear. http://www.fao.org/docrep/003/X6845E/X6845E04.htm
Macroalgae	Large algae, e.g., kelp. (FAO)
Mariculture	Mariculture: Cultivation, management and harvesting of marine organisms in the sea, in specially constructed rearing facilities e.g. cages, pens and long-lines. For the purpose of FAO statistics, mariculture refers to cultivation of the end product in seawater even though earlier stages in the life cycle of the concerned aquatic organisms may be cultured in brackish water or freshwater or captured from the wild. (FAO)
Marine primary production	The transformation of chemical or solar energy to biomass. Most primary production occurs through photosynthesis, whereby green plants convert solar energy, carbon dioxide, and water to glucose and eventually to plant tissue. In addition, some bacteria in the deep sea can convert chemical energy to biomass through chemosynthesis. (FishBase)
Microplastics	Plastics that enter the oceans in the form of small particles, as opposed to larger plastic waste that degrades in the water. Sources of primary microplastics include car tyres, synthetic textiles, marine coatings, road markings, personal care products, plastic pellets and city dust. https://www.iucn.org/news/secretariat/201702/invisible-plastic-particles-textiles-and-tyres-major-source-ocean-pollution-%E2%80%93-iucn-study
Necrosis	Sum of the morphological changes indicative of cell death and caused by the progressive and irreversible degradative action of enzymes; it may affect groups of cells or part of a structure or an organ; necrosis may take different forms and be associated with saprobionts (bacterial, fungal or protistan) proliferation. (FAO)
No-take zones	Sections of intertidal or subtidal terrain and overlying water delineated and legislated where no fishing or collection of certain species or groups of animals or plants can occur for a defined period. (FAO)

Oligotrophic gyres	Major cyclonic surface current systems in the oceans that are relatively low in nutrients and cannot support much plant life. (FishBase)
Pathogen	Any organism, which in living on or within another organism (the host) causes disease in the host. (FAO)
Pelagic ecosystem	Portion of the marine realm living and feeding in the open sea, that is, in the surface or middle depths of the sea. (FishBase)
Phenotype	Physical or external appearance of an organism as contrasted with its genetic constitution. Measurable/observable character of an individual. (FAO)
Phytoplankton	Minute plants suspended in water with little or no capability of controlling their position in the water mass; frequently referred to as microalgae (the plant component of plankton). (FAO)
Polyploid	Cell or organism having three or more sets of chromosome. Opposite: haploid; diploid. (FAO)
Reduction fishery	<p>Fishery that uses, or 'reduces', its catch to produce fishmeal or fish oil rather than for direct human consumption. These fisheries typically target small pelagic (midwater) species like anchovies, herring and capelin. Other species lower down the food chain, like krill are also caught for reduction.</p> <p>http://blog.msc.org/blog/2017/03/22/reduction-fisheries-sustainable-fish-oil/</p>
Spat	Fertilized shellfish larvae, e.g. of oysters or mussels. Spat commence life as free-swimming individuals in the plankton, then 'settle' onto suitable substrates (a spatfall). (FAO)
Trophic level (TL)	Classification of natural communities or organisms according to their place in the food chain. Plants (such as macroalgae) and phytoplankton (producers) are TL 1; herbivores eat plants and are TL2; carnivores are of TL 3 or higher.
Water column	Vertical section of the sea or lake; the water mass between the surface and the bottom. (FishBase)



Annex 6. List of abbreviations

ARRAINA:	Advanced Research Initiatives for Nutrition & Aquaculture (FP7 funded project)
CAP:	EU Common Agricultural Policy
CCAMLR:	Commission for the Conservation of Antarctic Marine Living Resources
CDR:	Carbon Dioxide Removal
CFP:	Common Fisheries Policies
CSR:	Corporate Social Responsibility
DCF:	Data Collection Framework
DHA:	Docosahexaenoic acid
EASAC:	European Academies Science Advisory Council
EC:	European Commission
EEZ:	Exclusive Economic Zone
EMSY:	Environmentally-Sensitive MSY
EPA:	Eicosapentaenoic Acid
EU:	European Union
EUMOFA:	European Market Observatory for Fisheries and Aquaculture
FAO:	Food and Agriculture Organization of the United Nations
FEI:	Future Expectations Indicator
GESAMP:	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GIS:	Geographic Information System
GMO:	Genetically Modified Organism
HLG:	SAM High Level Group of Scientific Advisers
ICZM:	Coastal Zone Management
IDREEM:	Increasing Industrial Resource Efficiency in European Mariculture (FP7 funded project)
IMP:	Integrated Marine Policy
IMTA:	Integrated Multi-trophic Mariculture
IPCC:	Intergovernmental Panel on Climate Change
ITQ:	Individual Transferable Quota

LA:	Linoleic Acid
LC:	Long Chain
MEA:	Millennium Ecosystem Assessment
MMT:	Million Metric Tonnes
MSP:	Maritime Space Planning
MSY:	Maximum Sustainable Yield
MS:	Member State
MTC:	Mean Temperature of the Catch
NPP:	Net Primary Productivity
OA:	Ocean Acidification
OECD:	Organization for Economic Co-operation and Development
OMZ:	Oxygen Minimum Zone
OTEC:	Ocean Thermal Energy Conversion
PUFA:	Polyunsaturated n-3 Fatty Acid
RCP:	Representative Concentration Pathway
SAM:	Scientific Advice Mechanism
SAPEA:	Science Advice for Policy by European Academies
SDG:	United Nations Sustainable Development Goal
SLO:	Social Licence to Operate
SRM:	Solar Radiation Management
STECF:	Scientific, Technical and Economic Committee for Fisheries
TL:	Trophic Level
TURF:	Territorial Use Rights in Fishing
UN:	United Nations
UNCLOS:	United Nations Convention on the Law of the Sea
UNCTAD:	United Nations Conference on Trade and Development
UNFSA:	United Nations Fish Stocks Agreement
WBGU:	German Advisory Council on Global Change

Annex 7. List of figures and tables

- Figure 1.** The three major components of food security and their respective elements
- Figure 2.** Global marine landings and mariculture production
- Figure 3.** Marine food per-capita
- Figure 4.** How the natural production diminishes with increasing trophic level (TL)
- Figure 5.** Global marine catches with indications of major functional groups
- Figure 6.** Fractions of main resources in salmon feed in 2016
- Figure 7.** Global mariculture production of FAO groups of organisms in brackish and marine waters.
- Figure 8.** Comparison of meat production in agriculture with aquaculture and fisheries
- Figure 9.** Satellite Gao-Fen 2 image of the coastal area of Cang-nan county, Zhejiang province, Southeastern China, showing large-scale seaweed (*Pyropia*) mariculture farms
- Figure 10.** Trophic level of wild Atlantic salmon and farmed Atlantic salmon
- Figure 11.** Production efficiency of farmed Atlantic salmon in two full-scale cages.
- Figure 12.** World Penaeid Shrimp production over the past 15 years (in kg)
- Figure 13.** Large-scale integrated multi-trophic aquaculture in Sanggou Bay, east of Qingdao in the Shandong province, China
- Figure 14.** Projected alteration of oceanic fluxes and atmospheric events due to a changing climate in the coming decades
- Figure 15.** Estimated annual economic loss in sub-national regions of Europe in 2100 due to damages on mussel production under ocean acidification (© Newcastle University reprinted by permission of Taylor & Francis Ltd, <http://www.tandfonline.com> on behalf of Newcastle University)
- Table 1.** The annual production at different trophic levels in the ocean
- Table 2.** Comparison of captured and cultured main groups of marine organisms
- Table 3.** Optional new feed resources with LC n-3 rich lipids for fish feed
- Table 4.** European consumer perspectives on seafood from aquaculture
- Table 5.** Functions of open governance
- Table 6.** Summary of options for more food from the oceans
- Table 7.** Impact of increases in different forms of fishing and aquaculture on marine ecosystem services



Annex 8. Acknowledgements

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Annex 9. Public engagement and outreach

In line with its commitment to public engagement and outreach, the SAPEA consortium organised several events across Europe to engage the public with the topic.

Mat Fra Havet

Nøstebode, Bergen, Norway – 18 June 2017

To coincide with UNESCO Sustainable Gastronomy Day, the City of Bergen in collaboration with SAPEA and the Academia Europaea Bergen Hub, organised a day of food tasting followed by talks at Nøstetorget, Bergen.

This involved a full day of interaction with the public, raising awareness of different types of food from the oceans through stalls from food organisations and local restaurants. Well-attended public talks on the topic, with audience Questions & Answers took place in the afternoon and evening. The event concluded with a lively panel discussion with experts, exploring the question addressed in this report. Speakers at the event included Dr Matthias Kaiser (University of Bergen, SAPEA Working Group Member), Professor Røgnvaldur Hannesson (Norwegian School of Economics), and Inger Elisabeth Måren (UNESCO Chair at the University of Bergen).

The event featured on the Bergen County website, and several other local Norwegian websites. TV2, the largest commercial television channel in Norway, covered it, with a typical audience of around 700,000-800,000 people. SAPEA and other organisers also made extensive use of social media. A report of the public debate was published (Academia Europaea Cardiff Knowledge Hub, 2017a).

SAPEA's work on Food from the Oceans was also promoted at the Bergen Food Festival (1-3 September 2017), which drew an audience of around 30,000 in total.

Food from the Oceans at Cardiff International Food and Drink Festival

Norwegian Church, Cardiff, UK – 14-16 July 2017

This event was organised by SAPEA in collaboration with Academia Europaea's Cardiff Hub and other partners including the Learned Society of Wales, the Welsh Norwegian Society, the Hordaland County in Norway and Cardiff University. It was part of the Cardiff International Food and Drink Festival, which typically attracts around 80,000 people.

A Food from the Oceans stand raised awareness of different types of food from the oceans. Throughout the Festival, there were talks with experts, including a panel discussion on how more food can be obtained from the oceans in a sustainable way. There were many opportunities for the audience to ask questions of the experts, and

find out more about SAPEA and the European Scientific Advice Mechanism. A report on the public debate was published (Academia Europaea Knowledge Hub, 2017b).

Speakers at the events included: Professor Gunnstein Akselberg (Bergen University), Dr Arne Duinker (National Institute of Nutrition and Seafood Research), Dr Matthias Kaiser (University of Bergen, SAPEA Working Group Member), Ian Kinsey (fisherman and consultant), and Professor Daniela Schmidt (Bristol University, SAPEA Working Group Member).

Interaction and promotion of the event online (via the Academia Europaea Cardiff Hub, Cardiff University and SAPEA's website), including tweets by Cardiff City Council (over 14,000 followers) and Visit Cardiff (over 42,800 followers).

Professor Carina Keskitalo (Member of the Scientific Advice Mechanism High Level Group of Scientific Advisors) attended the events.

Nahrungsquelle Meer – Entwicklungen, Gefährdungen, Prognosen


Baseler Hof Säle, Hamburg, Germany – 5 October 2017

As part of the German Wissenschaftsjahr 2016-17 – Meere und Ozeane (German Year of Science 2016-17 – Seas and Oceans), the Union of German Academies of Sciences and the Academy of Sciences in Hamburg, collaborated with SAPEA to organise a public panel discussion on Food from the Oceans in Hamburg.

The interdisciplinary panel debate focused on questions surrounding the sustainable generation of food from the oceans, in the context of Germany and internationally. The event attracted around 120 audience members, who were given the opportunity to ask for clarifications and views from experts.

Speakers included Dr Gerd Kraus (Thünen-Institut für Seefischerei in Hamburg), Prof. Dr Marian Paschke (University Hamburg, Member of the Akademie der Wissenschaften Hamburg), and Dr Gesche Krause (SAPEA Working Group Member).

Professor Rolf-Dieter Heuer (Chair of the Scientific Advice Mechanism High-Level Group) attended and presented at this event, together with Professor Ole Petersen (SAPEA).



Spanning the disciplines of engineering, humanities, medicine, natural sciences and social sciences, SAPEA brings together knowledge and expertise from over 100 academies, young academies and learned societies in more than 40 countries across Europe.

SAPEA is part of the European Scientific Advice Mechanism (SAM), which provides independent, interdisciplinary and evidence-based scientific advice on policy issues to the European Commission. SAPEA works closely with the SAM High Level Group of Scientific Advisors.



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