Food from the Ocean

– Norway's Opportunities

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Preface

This volume contains the written versions of the talks presented at a symposium with the title: "Food from the Ocean – Norway's Opportunities", jointly organised by the Norwegian Academy of Science and Letters (DNVA) (www.dnva.no), the Norwegian Academy of Technological Sciences (NTVA) (www.ntva.no) and the Research Council of Norway (RCN) (www.rcn.no). The symposium was held in the House of the Academy (DNVA) in Oslo on 30th January, 2013 and had 150 participants. His Majesty King Harald V attended the complete meeting.

Kristin Halvorsen, Minister of Education and Research, gave the introductory talk. Experts invited by the learned societies contributed with talks on future values created from the oceans, ecological principles of food production, biological systems understanding spanning the dimensions from the genome to the phenome, growth and innovation in global aquaculture and, finally, the Government's HAV21 report.

The following participants contributed by discussion and comments to the talks: Roald Dahl jr. (consultant), Sigmund Grønmo (University of Bergen), Geir Lasse Taranger (Institute of Marine Research), Reidar Toresen (Institute of Marine Research), Eric Thompson (University of Bergen), Kjetil Hindar (NINA), Liv Holmefjord (Directorate of Fisheries), Per Olav Skjervold (Vitenparken Campus Ås), Øyvind Påsche (Bergen Marine Research Cluster), Erik Sterud (Norwegian Salmon Rivers), Roy H. Gabrielsen (University of Oslo), TV2, and Kjell Naas (Research Council of Norway).

Together, DNVA and NTVA represent the entire spectrum of the learned disciplines. RCN is the Government's adviser in science issues. By the organisation of an annual symposium series like this, focusing on a subject of high political priority, the two academies and RCN want to develop this kind of science communication.

Previous symposia in the series: Marine Transport in the High North, held on 19th October, 2010; Norwegian Energy Policy in Context of the Global Energy Situation, held on 1st February, 2012.

The scientific committee of this year's Symposium: Professor John Grue (University of Oslo) (Chair), Director Christina Abildgaard (RCN), CEO Karl A. Almås (SINTEF Fisheries and Aquaculture), Professor Roy Helge Gabrielsen (University of Oslo) and Executive Director Fridtjof Unander (RCN).

We acknowledge with gratitude the assistance by Mr. Adrian Read, acting as Editorial Assistant of this publication, and Mr. Eirik Lislerud of DNVA, for taking on the practical matters with the organisation of the Symposium. The Symposium was jointly funded by DNVA, NTVA and RCN.

Some words about the chapters of this Volume:

Chapter 1 by Lisbeth Berg-Hansen, Minister of Fisheries and Coastal Affairs, reviews Norwegian and global aquaculture and views the industry from a research perspective. She writes that the success story of Norwegian fish farming should be further developed, and thereby contribute to increased food production and food security in the world. Strong growth is expected in the farming of salmon, new aquaculture species and in the production of marine ingredients. The seafood industry is described as one among three industries in Norway that can be developed into a global knowledge hub. Regarding Norwegian aquaculture research today, the most important areas in terms of funding are 1) feed, feed resources and nutrition, and 2) health and diseases. Themes that should have priority include: coastal ecosystems and their resilience; multipurpose use of coastal areas; aquaculture technology; seafood, seafood quality and animal welfare; and new resources for marine food, ingredients and fish feed. The recommendations for research provided in the HAV21-report are referred to (cf. Chapter 6 of this Volume). Opportunities for growth along the coast should be stimulated. A White Paper for the Parliament ('Verdens fremste sjømatnasjon', St. Meld. 22, presented on 22nd March 2013) points to the potential for harvesting and production from renewable marine resources, which is much larger than what we are utilising today. Knowledge and skills are prerequisite for future development.

In Chapter 2, Karl A. Almås of SINTEF Fisheries and Aquaculture provides a summary entitled 'Values created from productive oceans in 2050'. This refers to a report presented by the The Royal Norwegian Society of Sciences and Letters (DKNVS) and NTVA in 2012. Based on the progress of fisheries and the marine industry in recent years as well as megatrends in the world economy, the overview gives estimates and predictions for how the marine industries will be in 2050. It is estimated that the Norwegian aquaculture and fisheries industries together will produce a volume that is five times higher in 2050 than today, with the main growth coming from aquaculture. Topics that are discussed in detail include: marine industries in 2050, the fisheries sector, the salmon industry, marine ingredients and marine bioprospecting, feed production, the supplier industry, new species for human consumption, algae and highly productive waters. The need to attract the best people to the industry is stressed.

In Chapter 3, Yngvar Olsen of NTNU writes about ecological principles of seafood production. While the primary production in the terrestrial and marine biospheres are comparable in size, 98 per cent of human food comes from agriculture and only 2 per cent from fisheries and aquaculture. He illustrates the far less efficient marine production as follows: In the marine food chain, phytoplankton represents the primary production in the ocean - trophic level 1; zooplankton are on trophic level 2; molluscs, herring and sardines that are gazing on the zooplankton are at level 3; cod are at level 4; tuna, wild salmon at level 5, etc. In the transition between each level, 90 per cent of the energy and carbon consumed by an animal is lost back into the environment as CO_2 and organic components. This means that only 1 per mille of the marine primary production is available from cod on level 4 and only 0.1 per mille from tuna on level 5. For comparison, human food from agriculture basically comes from plants corresponding to tropic level 1. To increase the production efficiency of marine food one should harvest lower in the food chain. More plants and micro-organisms should be used for feed in aquaculture. Regarding salmon production there is a need to establish new bio-resources for food, moving salmon to a lower level in the seafood chain. While a farmed salmon today consumes half of the marine resources compared to a wild salmon, this ratio will most likely fall to 1:8 in the future.

In Chapter 4, Stig Omholt of NTNU, and Arne B. Gjuvsland and Jon Olav Vik, both of the Norwegian University of Life Sciences, propose a new large-scale research programme in Norway: 'The Digital Salmon Programme'. They seek an improved systems understanding of salmon biology with a causal bridge between the genome and phenome as the ultimate goal. In an effort to mathematize biological research, they suggest a merger of expertise from life sciences, mathematical sciences and engineering. They describe how the Digital Salmon Programme may help to preserve the wild salmon populations. They seek inspiration from international research efforts, such as the Virtual Physiological Human, a revolutionising pan-European effort of 21st century bioscience. Another reference is the World Wide Physiome Project.

In Chapter 5 Ragnar Tveterås of the University of Stavanger discusses growth and innovation in global aquaculture. During the last decades this industry has proven to exhibit the fastest growing food production technology in the world, and one is talking about a blue revolution. While the global production has increased from 1 million tons in 1955 to incredibly 79 million tons in 2010, the growth rate of the industry is currently slowing down, a decline that is slower in developing compared to developed countries, however. Externalities such as diseases and emissions are main reasons for the decline. Genetic innovation, primarily through fish breeding programmes, has to be a source of productivity growth where consumer acceptance is crucial. Innovations will allow for productivity growth and become translated into reduced production costs. This is historically a central cause of the global growth of aquaculture production. The production should develop towards 'biological manufacturing' including advanced control of the many processes involved.

In the final Chapter 6, Liv Monica Stubholt of Kvaerner ASA briefly describes the 'HAV21 report, an R&D strategy for a marine nation of substance'. The premises and the main recommendations of this report are described. The main subjects include: funding of research and development; legal perspectives, management and use; knowledge about the ecosystem; the Arctic and northern areas; harvesting and cultivating new marine raw materials; fish health and sustainable, safe and healthy seafood; food and markets; technology; interdisciplinary research; education and training programmes; and communication activities.

In total, the conference presentations cover important aspects of food production in the ocean environment. Besides the overview and trends of the industry, the research dimension in aquaculture is particularly highlighted. We do hope that this book will serve as a contribution in bringing the debate about this extremely important issue forward.

June 2013, John Grue and Karl A. Almås

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Introduction – Norway, a Maritime Country and a Global Seafood Producer

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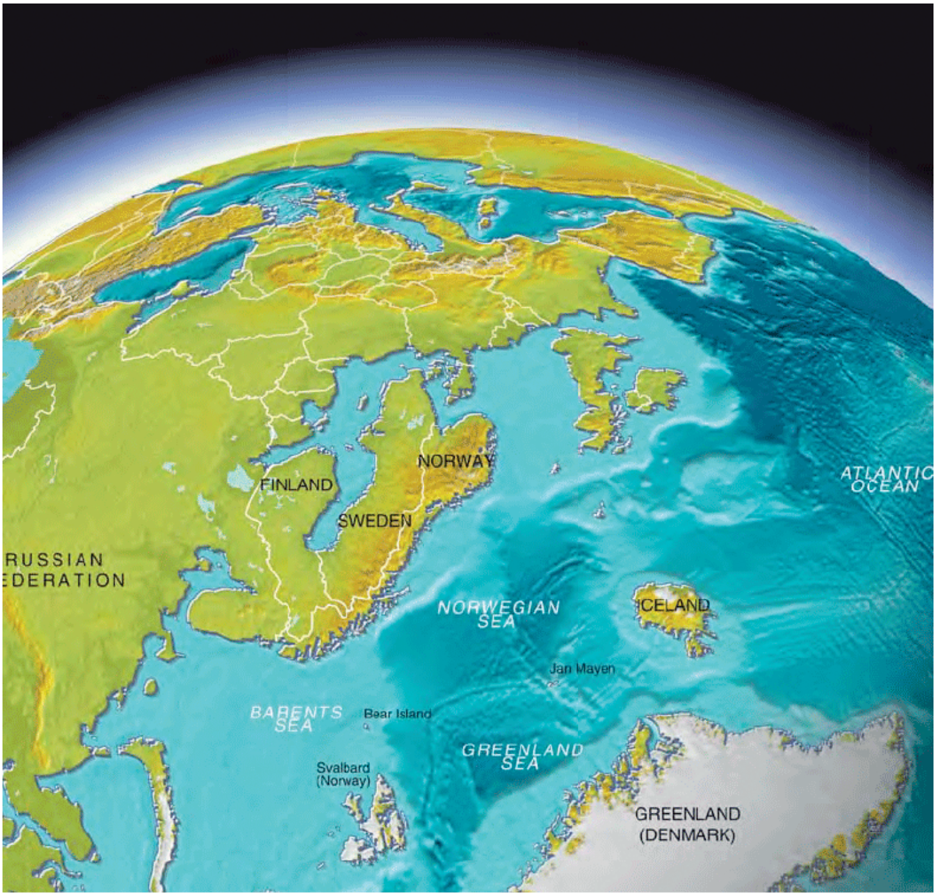
The fact that Norway is closely tied to the sea has more than anything contributed to the development of this country. The utilisation of the coastal areas has been of great importance for the survival and income of the people of Norway throughout our history. The enormous sea area that surrounds Norway is more than 5 times larger than the land areas under Norwegian jurisdiction (illustration).

Our dependence on the oceans for further economic and social development is stronger than ever. Reve and Sasson in "*Et kunnskaps-basert Norge*" ("A knowledge-based Norway"), Universitetsforlaget 2012, conclude that today Norway has three industrial sectors with the potential to become so-called "global knowledge hubs", which is the criterion for a sector to achieve export-driven success in the long term. These are industries which can act as driving forces in terms of know-how, have access to capital and operate in a global market. All three are related to the sea. The first of these is the offshore-based oil and gas industry, primarily the supplier and service sectors. The second is the maritime sector, which is also linked to the offshore sector to a greater extent than



in the past. The third is the seafood sector, which now of course also incorporates aquaculture and other biomarine industries in addition to the traditional fishing industry.

The seafood industry with its fisheries traditions has "always" been with us, and the present fishing industry has evolved through many centuries. In a global context, Norway is well-recognised as a fishing nation and reputed for its sound management and efficient fishing practices. However, the fisheries have neither had the need for, nor have they demanded, the same high levels of political resolution in decision-making as the oil and gas sector.

The aquaculture sector has grown during the same period as the oil industry, but has not enjoyed the same powerful policy facilitation as the oil and gas sector. Fish farming has expanded tremendously along the coast and has made Norway a leading producer of farmed salmon. Norway has gradually established a very strong position in Arctic waters, largely by virtue of the presence of its fisheries industry in these areas. Norway is also well-known in the rest of Europe as a major power in terms of its exploitation of marine resources and developing new biomarine industries.

In 2012 the Royal Norwegian Society of Sciences and Letters (DKNVS) and the Norwegian Academy of Technological Sciences (NTVA) published a report: *"Verdiskaping basert på produktive hav i 2050"* ("Value created from productive oceans in 2050") (www.ntnva.no). The report discusses in detail the potential growth within the marine industries of today and the new industries of tomorrow.

Our ability to extract future potential resources will depend to a great extent on several external factors. The marine sector must be given the necessary support within the future development of Norwegian industry. In Norwegian waters, priority must be given to food production in areas where the natural conditions are suitable for increased production. This will require management regimes based upon scientific knowledge, where optimal use of an area for food production is prioritised.

How can we realise the marine potential?

The Norwegian Minister for Fisheries and Coastal Affairs, Lisbeth Berg-Hansen, has made it clear that it is Norway's aim to become the world's leading seafood producer. It is pointed out that the expanding ambitions should also incorporate affiliated industries such as the supplier sector and the marine ingredients industry, as well as industries based on marine biological resources which are currently seen as embryonic, including the service-based industries.

On the basis of the perspectives discussed in the DKNVS-NTVA report mentioned above, ten recommendations were given to develop the potential into industry and further value creation:

- *Prioritise businesses.* Businesses enjoying comparative advantages must be supported to a greater extent than is currently the case. The marine-based industries must be assigned higher priority by Norwegian politicians.

- *Natural resource advantage.* Compared with other nations, Norway's oceanic and coastal resources represent unique natural advantages. These advantages mean that Norway must assume a particular responsibility for the production of food, feedstuffs for the fish farming industry, and other vital intermediate products based on marine biological resources.

- *Management of the oceans and coastal areas*. The future development of, and focus on, a knowledge-based coastal and ocean management system will be vital if Norway is to realise its value generation potential from biomarine resources. Management expertise is also in demand in other countries which want to consolidate their practices in this field. Norway should aim to strengthen its position as a world leader in the management of coastal and oceanic areas by investing in the systematic development of skills and expertise.

- *Policy framework for business activities*. Future value generation based on marine biological resources will depend on the maintenance of robust value chains within the aquaculture and fisheries sectors which are currently large volume producers, thus generating major value. Both the traditional value chains and the new developing marine industries must be competitive in global markets. A stable policy framework is a key factor here. The current framework must be reviewed with a view to creating a policy regime which meets the industry's demands for predictability and permits a certain level of flexibility.

- *Embryonic and new industries*. Embryonic and new industries based on marine biological resources have great potential, but will require other and more effective leverage than the current core industries, given the way in which they are described in this report. The use of drawback funds in the same way as in industries such as the oil and gas sector, access to seed corn and venture capital, clear efforts in terms of policy implementations which can mitigate risk, simplification of the policy implementation regime and consolidation and development of large and small-scale testing facilities, all represent important actions to achieve development.

- *An industrial super cluster.* Establish a world-class super cluster or "Global Centre of Expertise" to exploit the expertise located at the interface between the three global knowledge hubs: the maritime, renewable energy/petroleum, and seafood sectors.
- *Investment in R&D*. Businesses within the sector must invest in R&D by employing personnel with R&D expertise, implementing self-financed R&D projects, and becoming demanding commissioners of research at domestic and international research institutes. Norway as a nation ought to direct more public funds towards research and development in the marine sector.
- *Attract talented personnel*. In order to fulfil its great potential for value generated, the industry must become attractive to the best talents to a greater extent than is currently the case. A trend towards larger business entities will make a positive contribution since larger businesses more commonly demand more personnel with higher educational qualifications and generate real career paths for their employees.
- *Demand-driven education system*. The vocational education system directed towards the marine sector must be reviewed continuously and adapted to the sector's needs. The educational structure must be evaluated with a view to establishing the world's best marine-related education system. The education institutions and companies must develop a strategy to address the food challenge of urbanisation.

- *Technology strategy*. There currently exists no co-ordinated technology strategy in the field of the exploitation of marine resources. Such a strategy should be established. The export of marine technology and expertise is a field with great potential. It should be possible to combine Norwegian aid efforts with initiatives designed to create opportunities for the Norwegian seafood sector (supply industry, skills and expertise).

Our responsibility for food for the future

In recent years the marine sector has enjoyed a higher status than previously within the Norwegian economy. The fish farming sector has become increasingly visible in coastal waters and many more commentators than before are expressing their opinions about the industry. The Norwegian marine sector is to an ever-increasing extent dependent on both global and domestic development trends in society as a whole.

The most important global development trend influencing the marine sector is the rising demand for food resulting from overall population growth, combined with increased purchasing power among the middle class in particular. The demand for seafood and other marine products is set to increase, and Norway is one of the countries which will be able to meet these demands given its natural advantages, expertise and established industrial base. The second important development where marine products can make a difference is in relation to meeting global health challenges linked to unhealthy diet, obesity, and the demand for marine oils and other marine products.

The development trends outlined above represent opportunities but also potential threats to future growth in value creation in the marine sector. In fact, all these trends may represent threats if the development continues in directions which are unfavourable to the marine-based industries. Some threats may be difficult to influence, such as:

- Climate changes which may take a more dramatic course than anticipated to date.
- A global economic recession with long-term consequences.

- Stricter trade barriers resulting from a global economic recession.
- Reduction in the quality of the marine environment due to factors such as pollution.

However, our ethical responsibility for utilising our marine resources for the best to mankind should not be hindered by fear of global threats where our impact is limited, or by threats *(”Black Swans”)* that we do not see today.

Fish for the poor

One cannot talk about fish for the growing world population, particularly for the growing middle class, without addressing the dimension of fish for the poor. The situation of poor people may be illustrated by the cover story of the November Issue of *National Geographic* in 2012. The article describes the life of the people on Cuba and the economic situation there. One of the dimensions that is described, is the search for daily food. One characteristic term of that search is: “pollo por pescado’” meaning chicken for fish. While the family has been promised fish for dinner, there is no fish left in the shop, however, and the only food for the main meal is chicken. Surrounded by water, Cuba has its fisheries. However, the fish is sold to the restaurants, the hotel buffets or to private homes which can pay. According to the article, 80 per cent of Cuba’s work force has a monthly salary in the range 250-900 pesos, corresponding to 10-36 USD, and the fish is too expensive for an ordinary household.

The production and consumption of fish in a globalised food economy and how the trends in the fishery sector will affect the poor in the decades ahead, are among questions that are analysed by, e.g., the International Food Policy Research Institute (IFPRI) (www.ifpri.org) and the World Fish Center (www.worldfishcenter.org). Numbers and facts published by these institutions in: “Fish to 2020: Supply and demand in changing global markets” and “Outlook for Fish to 2020: Meeting global demand”, an accompanying food policy report, conclude that global consumption of fish was doubled during the 26 years from 1973 to 1997. Almost all of this growth has come in the developing world. Developing countries accounted for 73 per cent of the world production and 69 per cent of the global consumption of fish in 1997, up from 43 and 45 per cent, respectively, in 1973. Wild fish catch is near maximum of sustainable exploitable level. Further growth in global fish production must come from aquaculture. Due to the low growth in wild fish capture, the level of aquaculture production will contribute considerably to determine the relative prices for fish products. As a consequence of a strong increase in demand and slow increase in production, the real prices for most fresh and frozen fish has increased, contrary to most foods of animal origin where the prices have dropped during the last decades.

Fish will continue to remain expensive, compared to other food products, according to IFPRI. However, model calculations from IFPRI also show that a more rapid aquaculture expansion may contribute to a fall in predicted, future real prices of low-value food fish, but that prices of fish meal will increase. One of the scenarios described by IFPRI, where the price of fish meal is reduced, depends on improved efficiency in fish meal and fish oil conversion through rapid technological development.

Regarding fish for poor people, the reports write that this group faces new barriers in both their production and consumption of fish.

Regarding production and catch, landless fish workers and artisanal fishers are often among the poorest among people, even by the standards in developing countries. They operate on a small scale and use traditional capture methods. New methods and technologies that also meet environmental requirements can favour large scale capital intensive operations, but at the cost of traditional and small scale commercial fisheries.

Regarding fish trade, this has an increased importance and impact. In order to meet consumers' concerns regarding food safety of fish, developed countries have issued non-tariff trade barriers. New requirements relate to product documentation, hygiene, food safety and reasonable conditions for workers and the environment. New requirements usually imply new investments. Developing countries with the ability to make improved steps regarding fish food quality, may have the opportunity to increase their share in the lucrative export market. The reports write that there is a political challenge in finding new avenues, in order that small-scale producers can benefit from the profitable fish trade.

Regarding prices, these are increasing for the low-value fish typically consumed by the poor. This is a real policy concern since, from a nutrition point of view, even a small amount of fish is an important dietary supplement for people that depend on starch diets and have problems affording animal proteins.

Several publications discuss production, demand and prices of high-value fish species. One example is the report "*Fish Consumption Patterns in Asia and Europe*" published by The Fish Site (www.thefishsite.com) on 19 Sept 2010. Some conclusions of this report are:

- The increased demand in developed countries where the urbanisation is great, has first and foremost been for expensive (high-value) fish species.
- A similar trend, with request for high-value species, may occur in developing countries, as urbanisation increases.
- Particularly high growth rates have occurred in the production of high-value and carnivorous species.
- The increased production and supply of high-value species has contributed to a reduction in the market price.
- Some examples from the report include: The rapid production increase in whiteleg shrimp has contributed to a price depression in the international markets. The farm-gate value for 15-20 grams whiteleg shrimp declined from USD 5/kg in 2000 to USD 3-3.6/kg in 2005. The market prices for European sea bass and gilthead sea bream, imported to Italy from Greece, fell from Euro 7/kg in 1999 to Euro 4.6/kg in 2007, and from Euro 6/kg in 1999 to Euro 3.8/kg in 2007, respectively.

These cost reductions are promising with regard to fish for the total world population including the poor. Particularly the latter report offers some promise that new research and new innovations may contribute to an enhanced seafood production that is affordable not only for the wealthy but in the future also for those with limited means.

Particular research questions and motivation for the seminar

Although the primary production on land and in the ocean are of similar size, 98 per cent of human food comes from agriculture and the remaining 2 per cent from fisheries and aquaculture. With the fisheries being at their yield limit, the potential for increased harvest from the ocean environment comes from aquaculture. But how should research be focused in order to help increase seafood production?

More specifically, it is well known that an enhanced output is obtained by harvesting lower in the food web. When it comes to salmon farming this means searching for a fish that to some extent lives on plants and micro-organisms. What research directions should be pursued in order to achieve such a goal?

Gene research is a crucial dimension of fish farming. While scientists are able to gene sequence (fish) species, the next research question relates to how this detailed information can be combined with, e.g., the total physiology of the animal? Further, is it possible to make, e.g., mathematical simulations of diet experiments in fish farming?

In the dimension of fish for both wealthy and poor: Along which roads should we stimulate innovation and productivity growth and thereby reduce production costs in aquaculture?

Challenges and Opportunities for Norwegian Aquaculture – A Research Perspective

Lisbeth Berg-Hansen
Minister of Fisheries and Coastal Affairs

Since the early 1980s, the Norwegian seafood industry has experienced no less than a revolution in terms of volumes produced and technologies applied. This development can be attributed to many factors, but some of the more important are growth in fish stocks, innovations, broad productivity growth across the board in the marine sector, and perhaps most important, the establishing and incredible growth of salmon aquaculture.

In this brief article I will consider the significance of knowledge and science in the development of Norwegian salmon aquaculture. I will briefly describe the historical background of the development of Norwegian aquaculture, the contributions from research, and some lessons to be derived from this experience. Furthermore I will discuss global demand for food and what this demand entails in terms of opportunities for aquaculture, provide a brief overview of current aquaculture research and discuss how this research may develop in the years to come. Finally I will discuss the long term prospects for the industry, and the importance of attracting young professionals into this very exciting field.

Salmon – a novel farm animal

The Norwegian aquaculture adventure has been able to develop for four major reasons: resource-based advantages, experience from fisheries, creative pioneering work, and bold and explorative research at the interface between agriculture and the marine sector.

The most ancient documentation of fish cultivation in Norway can be found on a rune stone from probably around 1200, that reads, “Eilif Elg brought fish to Raudsjøen”. This indicates that a man of the Viking era called Eilif Elg carried trout to the lake “Raudsjøen” in Gausdal, in anticipation that they would grow and proliferate there, so that fish could be caught in the future.

Modern aquaculture took off much later, around 1970, and was based on the outstanding and exceptional characteristics of the Norwegian salmon and a thorough understanding of, and ability to manage, its reproductive phase. Salmon was a lucrative species for cultivation purposes and had a high market value. The eggs of the salmon are large and extremely sturdy, adapted to rough conditions on the gravel beds of turbulent rivers. Hence they were much simpler to handle in cultivation than the delicate roe of species like cod and halibut. Long before the start of salmon farming, experience had been gained with salmon cultivation in the rivers, and also pond cultivation of brown trout and rainbow trout.

Without resource-based advantages in the form of suitable coastal areas and a tradition for utilisation of the sea, aquaculture would probably never have become such a large industry in Norway. Other basic conditions were skilled pioneering workers and bold investors. The first and crucial step was that ingenious inhabitants of the islands of Hitra and Frøya experimented and found it was possible to grow salmon in cages in the sea. These first practical experiments with salmon aquaculture included feeding the fish with whole or minced fish (wet feed).

The second step took place in the research community. The scientific challenge was to transform salmon and rainbow trout into a novel farm animal, comparable to cattle, pigs and poultry.

The first generation of fish feed for salmon was quite crude. A large portion of the feed dissolved in the water, and there was at that time no scientific knowledge of the dietary requirements of salmon which could be used as a basis for designing a better feed. At the Agricultural University of Ås, pioneer researchers in the field of animal nutrition took this as a scientific challenge. Nutrition and feed production was a well established field of animal science, and the scientists adjusted the methods applied to traditional farm animals to this new aquatic farm animal. The first studies in salmon nutrition were initiated and thus began the development of a commercial dry feed that could meet the dietary requirements of the fish. One challenge was to develop a feed that would have the right composition in terms of macro- and micro-nutrients. Another was to have a feed that would not dissolve in water during feeding. The problem there was to develop good binders, or formulations, without negatively affecting digestion in the fish.

Another challenge was the genetics of the fish. Wild salmon show a wide variation between and within stocks in important economic parameters such as growth rate, feed conversion and age of maturity. From studies of other farm animals it is well known that such a variation is due to a large degree to genetic differences, which can be exploited for breeding purposes – the most important technology for productivity gain in domestic animal production. In the 1960s salmon was used as a model organism in breeding research. Researchers at the Agricultural University of Ås took an interest in this model organism, and concluded that breeding methods successfully applied in the breeding programmes for other farm animals could be transferred to fish. These researchers developed the world's first breeding programme for fish and this programme has had a major positive impact on the development of the modern salmon industry.

Disease and health challenges of aquaculture were encountered from the very start of the salmon farming industry. Application of pharmaceuticals was the immediate response, but it was realised relatively early that large scale application of chemicals would not be sustainable in the long term. Scientists at the Institute of Marine Research and the University of Tromsø were among the first to conduct research into the development of fish vaccines in the early 1970s. An abrupt drop in the application of pharmaceuticals was the immediate effect of the launch of this breakthrough technology.

The Fish Research Station at Sundalsøra was established in 1971, when the first 100 tons of farmed salmon in Norway was produced in the sea. The station became a central and powerful instrument for aquaculture research in the first phase of the development of the industry, primarily in the fields of salmon breeding and feed research.

Seafood exports from Norway amounted to 2.36 million tons in 2012. The value of this seafood export was more than NOK 50 billion, with approximately NOK 30 billion related to salmon/trout aquaculture and NOK 20 billion related to capture fisheries. Aquaculture production in Norway has grown over a forty year period from the 100 tons at Sundalsøra to 1.1 million tons in 2012. It is estimated that the whole seafood industry generates indirect offshoots for supplier industries and related activities in the order of 40% of its total turnover. Industries which benefit from this include the aquaculture feed industry, equipment and service providers, producers of biomarine ingredients, and suppliers of marine aquaculture species. The seafood industry today also generates considerable employment and income within public administration and the education and research sectors.

What can we learn from this success story? There are at least four main lessons:

1. **One has to have the courage to implement bold ideas and undertake innovative research**. There are setbacks and downsides, even fiascos, but major gains and solutions for the future may be the reward. Large amounts spent on aquaculture of purely marine species have not yet been very profitable in terms of industry development, but the public investment made in salmon aquaculture has proven to be immensely profitable.

2. **Curiosity across professional borders and transfer of established methodology to novel fields can be very rewarding**. We have to cross boundaries separating the various disciplines, and co-operate and learn from each other across the sectors. Application of animal science tools tested on domestic animals to a new fish aquaculture species may in hindsight appear a logical approach.

However, at the time this was not at all obvious, and partly a subject of ridicule by fellow scientists.

3. **Co-operation and exchange of knowledge between industry and research is a key factor**. When a company is an active participant in the research process, research-based and practical knowledge are brought together. Such a mix is extremely potent when it comes to the creation of new, innovative solutions and possibilities. When the first scientists got involved with aquaculture, they were keenly interested in the experience of the practitioners. They built their research on this experience, and tested the early results in close co-operation with these industry pioneers.
4. **International competition and co-operation is to be encouraged**. Research competition at an international level and in international settings is hard, and only the best succeed. However, such participation would foster the type of quality research which is crucial for an industry which aspires to become, and remain, a world leader.

The potential for Norwegian aquaculture

In 2050 there will be approximately 9 billion people on earth. According to FAO this implies that current food production will have to increase by 70% if everyone is to have an adequate diet. This scenario means that much more food will have to be produced. Almost all food consumed today is produced on land (98% according to FAO). However, access to fresh water and arable land is limited, and may be even more restricted due to climate change, continuous urbanisation and land and water degradation. Climate fluctuation, disease and low food stocks will probably also increase the risk for periods of food shortages, which may put vulnerable groups around the globe at risk. It is therefore a global challenge and a moral obligation to contribute to increased food production and food security. This point was heavily underscored in the final declaration from the Rio + 20 conference last year.

Because land resources available for agriculture are limited, an increasing part of world food production will have to take place in the oceans.

This was also widely recognised at the Rio + 20 conference. According to FAO, global seafood production was about 154 million tons in 2011. Capture fisheries supplied 90 million tons whereas aquaculture supplied about 64 million tons. 131 million tons were utilised for human consumption and approximately 23 million tons for non-food purposes. Looking at the food production potential of the oceans in general, ocean space is not a problem. However, productivity varies widely, from highly productive upwelling areas to open oceans with very low productivity. Supplies of seafood from wild stocks have levelled off, and many stocks are also heavily exploited. Aquaculture though has demonstrated a strong potential for further growth. FAO is therefore pointing to aquaculture as part of the solution to global food shortage.

Producing enough food to feed the world is a crucial issue. However, it is also important to be aware of the fact that today many more people are malnourished than undernourished. This is a global problem, and is on the increase. The connection between malnutrition, obesity and diseases like diabetes and heart disease and several others has been clearly demonstrated. Many would therefore argue that food quality and a healthy diet should be considered an integral part of the food security concept.

In this picture Norway has a very important role to play, as we have been extremely fortunate in terms of natural endowment. The ocean area of Norway is seven times the size of the land area and these oceans are also among the most productive in the world. We have a fisheries management system ranked among the best in the world and this, in combination with growth conditions in Norwegian waters which are currently very favourable, has contributed to excellent conditions for most of the commercial fish stocks. Growing conditions for salmon in coastal areas are also very good, which in combination with a whole package of professional skills has made it possible to develop what is probably the world's most effective aquaculture industry. On top of this it is now well known that a higher intake of fish and a larger proportion of fish in the diet could significantly improve the problem of malnutrition and diet-related diseases. This is why health authorities world-wide are recommending an increased intake of seafood.

A recently published report by SINTEF depicts a very promising future for marine value creation, indicating that sales from capture fisheries and aquaculture could increase from NOK 90 billion to NOK 550 billion over the next forty years. This scenario is based on an analysis of drivers and global megatrends. It foresees relatively modest growth in capture fisheries but strong growth in the farming of salmon and new aquaculture species, and in the production of marine ingredients. These factors in combination could add up to a six-fold increase in production in 2050 from the current sales level. Whether such a scenario can be realised is an open question, and as everyone knows the future is highly uncertain. However, it is clear that such a desirable development as described in the scenario would depend on certain preconditions. The interesting questions are what those conditions are, and to what extent such knowledge would be useful for policy and decision makers. According to "cluster theory", exceptionally successfully industries can be characterised by a combination of unique single factors and system properties which turn them into "global knowledge hubs". The question is whether such hubs can be found in Norway. According to a study by Drs. Torger Reve and Amir Sasson, "A knowledge based Norway", there are three industries in Norway which can be characterised as global knowledge hubs, and would have outstanding prospects to succeed internationally. These three industries are the ocean-based industries of seafood, the offshore industry and the maritime sector.

Aquaculture research today

Fortunately the Norwegian authorities have been positive about the possibilities of aquaculture. Even as early as the early 1970s salmon aquaculture became a research priority, and in the early 1980s was highlighted as one of four priorities for industry research.

According to an NIFU report from 2011, funding for marine research, aquaculture included, has tripled in ten years. Total funding for marine research in 2011 was about NOK 3.2 billion NOK. Aquaculture is at present a major field of research within the overall marine research area and has been developed through well-funded public research programmes and close co-operation between industry and the research community. Aquaculture research received NOK 1.4 billion of funding in 2011, more than NOK 500 million more than was reported in 2007. Aquaculture research received a 3.2% share of total R&D funding in 2011. About 43% of the research was carried out by the research institutes, 42% in the industry and the remaining 15% at the technical colleges and universities (UoH sector). NOK 1.1 billion was directed to salmon production research, and NOK 336 million to research on species new for marine aquaculture.

The two most important areas in terms of research funding in 2011 were a) Feed, feed resources and nutrition and b) Health and disease. More than 50% of aquaculture research funding was applied in these two areas, or approximately NOK 750 million. This focus was more pronounced for salmon aquaculture, whereas research for new marine species showed a somewhat broader thematic distribution and a stronger emphasis on production and management, and on larvae, fry and smolt. The programme area of Breeding and genetics increased sharply from 2009 – up from NOK 91 million, to NOK 151 million in 2011. Average yearly growth in this programme has been 7% for the period 2001-2011. The result of these efforts is that the Norwegian research community has an excellent research environment in this field. The major Bioscience Evaluation conducted by the Research Council in 2011, concluded that "Marine resources and aquaculture are of economic importance to Norway, and a number of research groups are undertaking high quality research in fields relating to marine ecology, including plankton biology, arctic marine systems, and marine genomics and biodiversity".

Another main conclusion in the NIFU report, under "Unique research possibilities in Norway" – 'Sustainable aquaculture products', is that "Norway has the expertise and track record for producing aquaculture products for the world. Norway can indeed take the global lead in demonstrating best practices in economically and environmentally sustainable ways" (of aquaculture production).

A good example of a recent Norwegian-led initiative is the "European Joint Program Initiative for Research on Healthy and Productive Oceans" (JPI Oceans). Such joint programmes are intended to contribute to coordination, appropriate division of work, and a greater degree of co-operation between the national research communities of Europe. Marine research is extremely costly and depends heavily on a sophisticated research infrastructure. There are major benefits to be gained from mutual co-operation and sharing of equipment and data. However, the biggest reward is that the limits of understanding and knowledge are continuously advanced, and that Norway is participating in, and in a position to influence, research priorities.

Much of the Norwegian economy is based on foreign innovations. The seafood industry is different because the innovations are of Norwegian origin. In several fields of this industry Norway is recognised as a world leader. Both technical skills and management experience are therefore in demand, and Norway has assisted countries like Vietnam, South Africa, Mozambique and recently, Brazil, in the development of sustainable management systems for their marine resources.

Research for tomorrow on its way

The government has recently received the R&D strategy "Hav 21" (Ocean 21), which is based on contributions and participation from all aspects of the seafood sector. The overall objective for this work has been "to design a better focused, coherent and co-ordinated national R&D approach in marine research". Ocean 21 is a broad and ambitious strategy which draws on the input from four different working groups, each dealing with a major area of marine research: management, fisheries, seafood and aquaculture.

The general recommendations for the aquaculture sector are:

- An international perspective should be applied to aquaculture research.
- Basic research links with applied science in the aquaculture sector should be strengthened.
- Incentives for multi- and cross-disciplinary research to be further developed.

- A strategy and an action plan for aquaculture research infrastructure should be prepared.

The following themes for research should have priority:

- Coastal ecosystems and their resilience.
- Multipurpose use of coastal areas.
- Aquaculture technology.
- Seafood, seafood quality and animal welfare.
- New sources for marine food, marine ingredients for pharmaceutical industry, health food, pet food industry, etc. and fish feed.

The Government proposes allocation of 45 new, so called “green”, salmon farming licences in 2013. Granting of these licences will be conditional on new approaches and innovations on sustainable aquaculture. I want to encourage the development of technical solutions as a driving force for positive change in the industry. This provides opportunities for growth along the coast, but most in the north of Norway, in the counties Finnmark and Troms.

I am currently preparing a White Paper to be tabled in Parliament shortly. In this paper I am proposing as a vision that Norway should be world leader in the production and export of seafood. The white paper will claim that the potential for harvesting and production from marine, renewable resources is much larger than we are utilising today. Knowledge and skills will be a central theme as these are a prerequisite for further development. The recommendations for research provided in the “Ocean 21” report will be a key input under this theme. Research provides the ideas and knowledge we do not have today, but need for tomorrow.

The future – and the younger generation

Some concluding remarks about a most important topic; the long term perspectives for Norwegian aquaculture. This is closely related to how we manage our human resources. The seafood industry will require employees with higher education, and research backgrounds. It is therefore vital that we manage to convince the younger generation that important challenges and an interesting professional career can be found in the marine sector. In this context I am particularly concerned about the opportunities for a scientific career. I think we should challenge the younger generation to participate in this important task of producing sufficient and healthy food for an increasing world population. We should also challenge them to get involved in the search for solutions as to how such production can take place in a sustainable manner.

This, I believe, can be done by actively encouraging young people to take an interest in the marine sector when deciding on which disciplines to study, and when choosing topics within their fields of interest. A varied selection of disciplines will be required in the marine sector both now and in the time to come, like biology, technology, ecology, economics, languages and foreign cultures. Secondly I think that the industry has to fully realise the potential of skilled young professionals and should vigorously promote the variety of job opportunities within this sector. On completion of their formal education it is vital that young professionals experience that their efforts and skills are appreciated, and that they can get employment in research or within the industry. A well-functioning co-operation between the research institutions and industry for the exchange of young professionals will be required if Norway is to become, and stay, a world leader in seafood production.

As the Danish saying goes; “big hooks are required to catch big fish”. My government is going after the big fish, and we are preparing the hooks!

Values Created from Productive Oceans in 2050

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Introduction

Norway has jurisdiction over sea areas that total more than 5 times the land areas. Throughout our history the utilisation of the coastal areas has always been of great importance for the survival, and income, of the people of Norway. Reve and Sasson (2012) conclude that today Norway has three industrial sectors with the potential to become so-called “global knowledge hubs”, which is the criterion for a sector to achieve export-driven success in the long term. These are industries which can act as driving forces in terms of know-how, which have access to capital and which operate in a global market. All three are related to the sea. The first of these is the offshore-based oil and gas industry, primarily the supply and service sectors. The second is the maritime sector, which is also linked to the offshore sector to a greater extent than in the past. The third is the seafood sector, which now of course also incorporates aquaculture and other biomarine industries in addition to the traditional fishing industry.

The oil and gas boom was launched with discoveries in the North Sea in the 1960s. Since then, resolute politicians, industrial leaders and the geoscience community have all contributed towards making Norway one of the most important oil and gas nations in the world. This was a determined and strategic process characterised by the commitment and determination of key individuals.

The maritime sector is the second of the important future-oriented industries. This sector has long traditions in Norway and has grown slowly but surely over the years. Norwegian ships, the Norwegian maritime supply industry and Norwegian seamanship are and have been renowned across the globe. The maritime sector has always been skilled in attracting the attention of politicians and in obtaining policy frameworks which have enabled the industry to remain competitive in the global market.

The seafood industry with its fisheries traditions has "always" been with us, and the present fishing industry has evolved through many centuries of tradition. In a global context, Norway is well-recognised as a fishing nation, and reputed for its sound management and efficient fishing practices. However, the fisheries have neither had the need for, nor have they demanded, the same high levels of political resolution in decision-making as the oil and gas sector.

The aquaculture sector has grown and developed during the same period as the oil industry, but has not enjoyed the same powerful policy facilitation as the oil and gas sector. Fish farming has expanded tremendously along the coast. Norway has gradually established a very strong position in Arctic waters, largely by virtue of the presence of its fisheries industry in these areas. Norway is also well-known in the rest of Europe as a major power in terms of its exploitation of marine resources.

Currently in Norway there is a political focus on opportunities for future value generation, and biomarine resources are part of this drive. This includes HAV21, a research-based strategic project initiated by the Government with the aim of promoting sustainable industrial development and sound management of the marine environment. A new Government White Paper addressing seafood issues which the Ministry of Fisheries and Coastal Affairs is in the process of preparing will be put before the Norwegian Parliament during 2013.

In 1999 the Norwegian Academy of Technological Sciences (NTVA) and the Royal Norwegian Society of Sciences and Letters (DKNVS) published a report entitled "*Norges muligheter for verdiskapning innen havbruk*" ("Norwegian opportunities for growth in the aquaculture sector"). The report focused on and described Norwegian opportunities for the development and exploitation of biomarine resources and predicted that in 2010 the total biomarine industry would represent a total market value of NOK 75 billion. The actual value turned out to be about NOK 80 billion.

In 2012 DKNVS and NTVA published a new report called *"Verdiskaping basert på produktive hav i 2050"* ("Value created from productive oceans in 2050"*)*. This report represents a sequel to the previously mentioned report, and outlines perspectives and opportunities which Norway now has, as one of the world's major nations in terms of its economic exploitation of the oceans, in the fields of cultivation and harvesting of the ocean's biological resources. The report estimates the total values created from productive oceans in 2050 to be NOK 550 billion, which is more than six times the value today.

The study covers a long time span, and it must be assumed that much of what it will be possible for us to take from the oceans in terms of resources in 2050 is currently unknown. Our ability to extract future potential resources will depend to a great extent on several external factors. The marine sector must be given the necessary support within the future development of Norwegian industry. In Norwegian waters, priority must be given to food production in areas where the natural conditions are suitable for increased production. This will require management regimes based upon scientific knowledge, where optimal use of an area for food production is prioritised.

The industry is also dependent on predictable conditions being set by the politicians, to reduce the investment risks. In order to develop the new and unborn biomarine industries, research and development within this sector must be significantly strengthened. Successful development of the biomarine industries is dependent on the recruitment of talented people, which will be a challenge in the years to come.

Marine industries in 2050

Based upon the assumptions discussed above, it is expected that in 2050 the marine industry will consist of different industrial segments. Value generation is represented by two principal areas of development:

- A progressive development of the seafood sector's currently familiar core industries.
- The development of embryonic and new industries.

Figure 1 below gives an overview of the nine different industrial sectors expected to contribute to the values created from productive oceans by 2050.

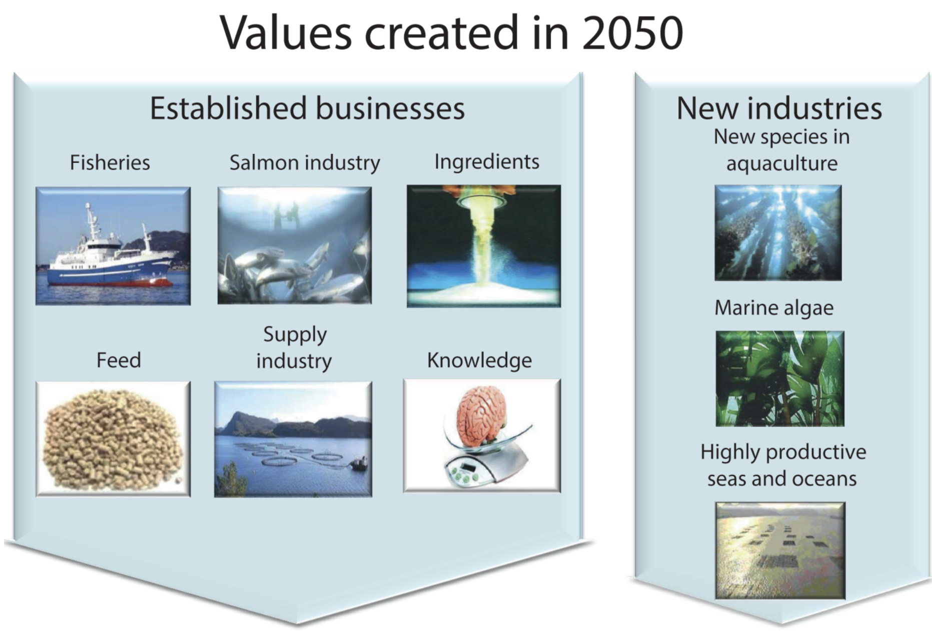

Figure 1. Values created in 2050: 550 NOK billion.

Today's industries:

- *Fisheries sector:* Value chains based on wild catch of pelagic species, whitefish (cod), flatfish, shellfish and molluscs.

- *Salmon industry:* Value chains based upon salmon and trout farming.
- *Marine ingredient industry*: Producing oils, proteins and marine biochemicals.
- *Fish feed production*.
- *Supply industry*: Technology to harvest, or to produce marine-derived products.
- *Knowledge:* Expertise in the form of the collective experience and know-how that currently exists within the industry, the public authorities and the research communities.

New industries:

- *New species (fish, shellfish):* Value chains based on the farming of other species such as cod, halibut, Arctic char and mussels.
- *Macroalgae:* The harvesting or cultivation/production of marine micro- and macroalgae (seaweeds).
- *Highly productive waters:* Extensive growth of seafood by cultivating sea areas.

The fisheries sector

The term "fisheries sector" is understood to encompass value chains based on the harvesting of cod varieties, pelagic species, flatfish and benthic species, shellfish and other molluscs, and shrimps. These value chains include links incorporating harvesting, processing and sales/export activities. This is the fisheries sector we are familiar with today, and in 2050 these species and value chains will continue to be part of the core activities within the marine industries. It is anticipated that in 2050 the industry will have begun to harvest species at lower trophic levels in the food chain, like krill (*Euphausia superba*) in the Southern Ocean, as well as attempt to harvest copepod species such as *Calanus finmarchicus* in Norwegian waters. Moreover, other species not currently considered to be of commercial interest, including marine mammals, will be caught and processed.

Norwegian waters and fishing practices

There is a given probability that in 2050 the coastal and oceanic waters managed by Norway will continue to be highly productive although there are major uncertainties linked to these prognoses. However, there is a certain consensus among climate researchers that, compared with many other countries, our waters will be positively impacted by climate change (Sundby, 2012). Marine pollution will contribute towards complicating this scenario, and in the future it will be necessary to boost levels of research into issues such as climate and ocean acidification.

Norway is already a world leader as regards the management of our fisheries resources, and we are putting major efforts into building up our knowledge base with the aim of developing management systems which are ecosystem-based. How can we utilise our marine resources based upon sustainability that extends across geographical borders and national jurisdictions?

Challenges facing harvesting practices will be linked to regulation of the catches and the quality of fish and shellfish, aimed at ensuring that species are not overfished. In the future this will be carried out as a joint effort between the research community, the industry and the authorities. New approaches and technologies will permit the continuous improvement of estimates and computations, provided that Norway, as a seagoing nation, prioritises public financing to maintain and boost the quality of research into its fish populations and the marine environment.

The economic value of total harvested volumes from our recognised fisheries is expected to increase in the years leading up to 2050. The reason for this is linked primarily to increased demand which is anticipated to come from a variety of different markets. Assuming that Norway successfully maintains its sound management practices, in addition to preventing accidents linked to its oil production from Arctic waters, seafood from Norwegian waters will continue to keep its excellent global reputation as unpolluted and healthy food.

Processing – at home, abroad or onboard?

In recent years, much of the profitability linked to the "harvesting value chain" has been connected with fishing fleet operations, while the processing sector onshore has struggled with prolonged periods of poor profitability. It is reasonable to question whether Norway will still have a land-based processing industry in 2050 or if such activities will be carried out in low-cost countries or onboard large factory vessels which harvest fish in Norwegian waters before proceeding directly to the markets which they serve. Overall, we can be certain that there will be value generation opportunities linked to the processing of fish in Norway. The value of waste raw materials must be realised, and developments in technology and expertise will be required both in the processing sector and among the suppliers. Logistics and traceability systems have to be improved.

The consumer decides

In 2050 our knowledge of individual consumers' wishes and preferences will dominate the entire value chain, including the fisheries. Fish are seen as a health-promoting product and are in demand among an increasingly growing and aware middle class with a willingness to pay. The quality of both fresh and frozen products has increased significantly, and shelf life has been prolonged. The range of products has increased and several "combination products" are available which bring together a variety of seafood groups and other foods. The price range is also much wider than today and consumers pay very good prices for high quality products. The consumer is increasingly concerned with product labelling, and information is communicated using advanced traceability and IT systems.

Production volume and economic value estimates for the fisheries sector

The criteria for achieving increases in catch volumes are linked to:

- Increased volumes of harvesting from lower trophic levels. Such activities will involve strict requirements in relation to documentation and sustainability.
- More species and sizes of fish and shellfish will be harvested than is the case today, and all will be brought ashore.

- Optimal management of current populations (ecosystem-based management).

The criteria for achieving increases in economic value in 2050 (an increase in excess of the production volume increase) are linked to:

- Increased scarcity of food combined with an increased desirability and demand on the part of the consumer to eat healthy products.
- More knowledge-based products.
- Increased purchasing power among the middle class worldwide.
- Increased profitability in the land-based industry due to increased levels of processing, automation, etc.
- Increased exploitation of, and higher prices received for, waste raw materials.

Fisheries	1999	2010	2030	2050
Economic value, billion NOK	20	27	32	50
Volume, million tonnes	2.7	2.7	3	4

Table 1. Estimated economic value and production in the fisheries sector.

The described development within the fisheries sector is based upon a further increase in relevant research activities. A sustainable harvest and utilisation of the wild fish resources will require new generations of harvesting systems and technology for optimal catch handling for serving consumer markets with the best quality seafood.

The salmon industry

The term "salmon and trout farming value chain" is understood to refer to breeding and broodstock activities, smolt production, the production of marketable size fish for human consumption, slaughter, processing and export and sales activities. Salmon is expected to continue to be the dominant farmed fish species in 2050. In recent years, trout production has stagnated somewhat, and more uncertainty is linked to the role that trout might play in future commercial fish farming activities.

Solving environmental challenges – a prerequisite for future economic growth

A prerequisite for salmon maintaining its position in 2050 as the dominant farmed fish species in Norway is that the industry and research communities find solutions to the environmental challenges set out in the Government's sustainability strategy linked to the genetic impact on wild salmon of escapes, disease (including parasites), pollution and discharges, area use and feed resources. The industry and the research communities are working to find answers in all these fields, and this work will be intensified in the years ahead.

In 2050 biotechnological and genetic methods have enabled the development of a sterile salmon with excellent growth properties and robust immune system. New net technologies have been developed and escapes of farmed fish have been eliminated. In 2050 we have achieved good control over the lice situation, as is already the case today in many locations. In addition to a vaccine against the salmon lice, work is continuing to develop biological and technological solutions. Fewer and larger fish farming enterprises are making it easier to successfully achieve joint initiatives and strategies in certain fields.

Even though we have resolved many disease-related challenges by means of ever-improved vaccines, nutrition and other preventive measures (less stress, sensitive handling), there still remain disease-related issues within the fish-farming industry, as with other domestic animals.

The greatest challenge in 2050 in terms of resources will be linked to access to high quality feed resources, and marine-derived resources in particular. Harvesting at lower trophic levels in the marine food chain has improved access to marine-derived feed resources, but here too there are constraints on what it is possible to extract. When it comes to land-derived feedstuffs, those produced with the help of GMOs are now permitted, but issues remain linked to quality and access. The competition for feed resources has become tougher.

Organisational changes and the strategic application of R&D

Solutions to the environmental challenges have been the result of more intensive and committed joint collaboration between the aquaculture companies, the supply industry and the research communities. The aquaculture companies have declined in number and those remaining are larger. In 2050 they have become demanding commissioners of solutions from both the supply industry and the R&D centres. In many ways they conduct their operations similarly to the way Statoil does today. They are granted concessions to operate fish farming facilities and assume responsibility for the fish themselves, for product development, sales, marketing, and customer relations. They have also made stakeholder acquisitions in large foreign customer enterprises. At the same time, the supply industry delivers goods and services linked to technology, feedstuffs, fish health and breeding products, as well as the establishment and operation of farming facilities. Many operations are highly specialised and require levels of expertise which it is inappropriate for the fish farming companies themselves to employ. Core expertise within the fish farming companies is linked to the feeding and care of the fish themselves. Moreover, the fish farming companies have accumulated high levels of research expertise and are significant and reliable commissioners of research work.

Diversification into a variety of production fields and approaches

In the years ahead a diversification of production approaches will take place in the fish farming industry. This will include the production of larger fish in the hatcheries than is currently the case, closed systems deployed at sea, and the exploitation of new and more exposed sites for the location of fish farms. Developments will take place largely as a result of stipulated environmentally-based restrictions on growth which in turn appear to promote an "inventiveness" needed for the industry to be able to produce greater volumes.

Increased levels of processing and the exploitation of waste raw materials

In 2050 it is most likely that all farmed fished will be filleted in Norway. We will also see the production of larger volumes of more highly processed products. Transport is significantly more costly than today. Moreover, waste raw materials have become valuable components in the marine ingredients industry. Waste raw materials for human consumption such as belly flaps and heads fetch higher prices and make a major contribution to the processing industry's bottom line. Oils derived from farmed fish are used both as feed for farmed fish and in other products. Levels of automation are high and production is driven mainly by process operators and robots.

Production volume and economic value estimates for the salmon industry
In 2050, the most important criteria for increased production are linked to the following:

- Resolution of the environmental challenges set out in the Government's sustainability strategy.
- Political will to promote the industry.
- Changes to the regulatory regime enabling the industry to experience a predictable strategic framework within which companies can make investments, and that these regulations do not restrict their opportunities to develop competitive businesses.
- Continued rise in market demand for salmon.
- New and important innovations in the fields of feedstuffs, fish health, breeding and technology.

The criteria for increases in economic value in 2050 are in many ways the same as those for the fisheries value chain (page 38), and are linked to the following:

- Increased scarcity of food combined with an increased desirability and demands on the part of the consumer to eat healthy products.
- Greater know-how built into the products.
- Increased purchasing power among the middle class.
- Increased prices for waste raw materials.
- Increasing levels of processing to produce fillets and other semi-manufactured products.

Fisheries	1999	2010	2030	2050
Economic value, billion NOK	20	27	32	50
Volume, million tonnes	2.7	2.7	3	4

Table 2. Estimated economic value and production in the salmon industry.

In the last two decades, the average annual growth in the production of salmon and trout has been just under 10%. It is unlikely that we will see the same levels of annual growth in the years leading up to 2050. Within the global aquaculture sector, annual growth in recent years has been 4% on average, and the FAO points out that real increase in future demand will be about 5.6% annually (Mathiesen, 2012).

Marine ingredients and marine bioprospecting

The term "marine ingredients" is understood to refer to value chains based on raw materials derived from Norwegian waters which contribute to the production of oils, proteins and biochemicals. In principle, there are three relevant raw material sources:

- Ingredients based on the harvesting and processing of a given volume of biomass:
    - Waste raw materials from the seafood industry.
    - Seaweed production and harvesting.
- Ingredients produced by specific organisms and identified by marine bioprospecting (exploitation of the genetic potential in the oceans for product development).

Industrial processes make use both of established process technologies that are more closely related to the foodstuffs industry, and more biotechnological processes, including marine bioprospecting.

The most important sources of marine ingredients in Norway today are the waste raw materials derived from the traditional fisheries and aquaculture industries. In 2011 waste raw materials amounted to 820,000 tonnes. Approximately 170,000 tonnes were used in the manufacture of consumable products and specialised products, while the remainder was used as feed in the form of fish meal, ensilage concentrates and feed for the fur industry. Approximately 180,000 tonnes of waste raw materials derived from the fishing fleets are currently not exploited at all.

In 2050 Norway will enjoy a strong position within the global marine ingredients industry and will manufacture products for the foodstuffs, functional food (marine oils, proteins), health food and pharmaceutical markets. These are global markets enjoying high levels of growth as they attempt to meet the health-related challenges linked to obesity and defective lifestyles. Global trends and a popular focus on health matters have made it possible to develop a leading and dynamic industry on the basis of marine-derived oils. This trend has made possible the growth of an industry which exploits proteins or protein molecule fragments such as peptides and amino acids in the manufacture of products which can function as antioxidants and as blood pressure and body weight regulators.

The most important criteria for the maintenance of a robust marine ingredients industry in Norway in 2050 are linked to the following:

- An increase in status and economic value of waste raw materials in the feed and consumer markets.
- Strong growth in profitable feedstuffs, foodstuffs, functional food, health food and pharmaceutical markets.
- An intense focus on research and innovation within both the private and public sectors within genetics, feed, technology and consumer trends.
- A robust source of raw materials from within the traditional seafood sector.
- New raw materials sources such as marine bacteria, and micro- and macroalgae.

Salmon industry	1999	2010	2030	2050
Economic value, billion NOK	12.1	34	119	238
Volume, million tonnes	0.5	1	3	5

Table 3. Estimated economic value and production in the marine ingredient industry.

Feed production

Almost all fish and shrimp-related species which are intensively farmed using formulated feed in the form of pellets, both in fresh and salt water, are fed with fishmeal as part of their feed, even if the proportions vary (1-35%). Salmonids, marine fish and shrimps, but not carp species, are also fed with fish oil (1-20%) as a proportion of dry feed. (Tacon and Metian, 2008, compiled by Olsen, 2011). The feed resources can be categorised as follows:

Current sources:

- *Harvested resources from the fisheries industry* (industrial fish 30-35 million tonnes annually).
- *Discard from the fisheries vessels and losses during processing* (no more than 50 million tonnes annually).
- *Agricultural products and waste* (large volumes).

Potential future sources:

- *Zooplankton* (large herbivorous species such as krill and copepods).
- *Macroalgae*.
- *Unicellular biomass:*
  - *Microalgae* (not as a bulk resource, but possibly as a source of DHA).
  - *Bacteria, yeast and genetically-modified organisms*.
  - *Thraustochytrids* (unicellular organisms, a possible source of DHA).
- *Agricultural waste* from both plants and animals.
- *Genetically-modified higher terrestrial plants* (sources of DHA and EPA).

Feed demand scenario 2050

Based upon the assumptions described in the sections above, Norway will in 2050 continue to be a global leader in salmon farming. Production volumes have increased steadily at about the same rate as in the years prior to 2010 and reached approximately 5 million tonnes. There is a demand for 6 million tonnes of feed pellets, an increase of 4.8 million tonnes compared with 2010. It will be possible to produce almost 1.2 million tonnes of new feed from marine-derived sources, released by the cessation of discard by the fisheries and the full utilisation of waste derived from the processing sector. New demands during the period from 2030 to 2050 amount to 2.4 million tonnes. We expect that regardless of other circumstances almost half of this volume must be derived from new resources.

The opportunities this creates will be crucial in the period from 2030 to 2040, and an essential prerequisite after 2050. If it becomes difficult to find new feedstuffs from known sources, including the fisheries and processing industries, groups of farmed organisms which do not require feed, such as molluscs and seaweeds, will become increasingly dominant within the global market, and the growth in fish and shrimp farming will be permitted to decline. It is important to note that salmonids appear to be metabolically flexible and exhibit more moderate requirements in terms of marine fats than many other fish species.

Feed production	2010	2030	2050
Volume, million tonnes	1.2	3.6	6

Table 4. Expected feed production.

The supply industry

The term “supply industry” refers to components in the form of goods and services which are essential either to the harvesting or processing of marine products. These goods and services represent a vital component of the Norwegian seafood sector. The most important components in terms of fishing activities are linked to vessels and vessel technologies, monitoring and control technologies, fishing gear, fuel, legal and business-related services. In terms of fish farming the most important components include feed, fish health products and services, transport services, technology in the form of equipment and buildings (sea cages, floats, onshore facilities and such like), and legal and business-related services. The processing of all fish species, inclusive of salmonids, cod varieties and pelagic species, has need of the same components. Areas of particular importance are processing technology (slaughtering, filleting and advanced processing lines), packaging and transport.

In addition to the supply of goods and services to the Norwegian seafood sector, technology and other commodities, including both fisheries and aquaculture-related technologies, are exported to several other countries. Increased levels of export activity are anticipated from suppliers to the seafood sector, in much the same way as the oil sector's supply industry exports equipment and expertise to the rest of the world.

The most important criteria for the maintenance of a strong supply sector in Norway in 2050 are linked to the following:

- Increased activity and production within the core industries (fisheries, aquaculture, etc.).
- Increased overseas demand for Norwegian aquaculture technology and expertise.
- Certain restructuring within the supply sector.
- Various enterprises find new ways of working even closer together to deliver integrated solutions.
- Policy makers must assign priority to strategies for the supply sector, facilitating the mitigation of risk linked to investment in new technologies.
- The supply sector must obtain even greater levels of input and know-how from affiliated industries.

The supply industry	2010	2030	2050
Economic value, billion NOK	23	69	124

Table 5. Estimated economic value in the supply industry.

Expertise

The marine industries are competing with other sectors for the best people. It is essential to make marine-related studies at the various educational institutions more attractive, and the industries themselves have a major role to play in achieving this. Their levels of in-house expertise are currently unsatisfactory for such knowledge-based enterprises, and highly qualified and expert personnel must be employed if the companies are to reap the benefit for value generation of the rapid advances in know-how taking place in the world outside, in the R&D communities and in the supply industries. For this reason the marine industry sector should find different ways of establishing closer ties with the educational institutions.

The challenges facing the marine sector and the authorities have become more complex, making it essential to adopt a holistic approach toward these issues. There is a need for a more multidisciplinary and trans-sectorial approach by which closer ties are established between the basic public and private sector research centres. The need for a major investment in resources, both in terms of the use of costly infrastructure and of research capacity, will result in the development of larger and more integrated projects.

Expectations of major levels of value generation, accompanied by better strategies for sustainable and environmentally sound exploitation of marine resources, are attracting increasing attention in international fora such as the World Bank. It is within these fields that the Norwegian contribution can be greatest in a global context. Norway is a major player when it comes to the transfer of know-how which contributes to global food security. Norway is regarded as a world leader in terms of management of its fisheries industry and marine resources. This is sought-after expertise and Norway is currently already exporting such know-how to a number of countries across the world.

New species for aquaculture

The production of new species in Norway for human consumption has the following trend possibilities:

Cod and halibut farming

Key issues such as feed, juvenile production and technology linked to cod production must be solved in order to reduce production costs to levels that enable the industry to become profitable. At the same time, farmed cod must be harvested during periods of the year when they provide a supplement to, and do not compete with, wild cod.

Other fish species
If industries linked to other fish species and shellfish are to achieve growth, significant levels of public funding must be allocated to support R&D and the commercialisation of existing expertise, the build-up of biomass, and marketing. Moreover, the industry must secure significant amounts of private sector capital.

Integrated multi-trophic aquaculture (IMTA) proving new opportunities.
Key criteria for growth within the IMTA mussel farming sector are as follows:

- There must be a demand and a market for Norwegian mussels – either in the form of an export market for human consumption, or a market for feed or other products.
- Aquaculture operators with the capital and appropriate expertise needed to establish facilities and build up biomass must be identified.
- New know-how must be developed in biology and technology to obtain environmental and economic sustainability.
- Veterinary restrictions linked to the distance between mussel beds and salmon farms must be liberalised.

Cleaning-fish, a natural approach to combating salmon lice.
Key criteria for growth within the cleaning-fish farming industry are as follows:

- Cleaning-fish continue to be regarded as an important method for combating salmon lice.
- The industry is successful in the cost-effective farming of cleaning-fish and in employing such fish in a responsible manner in terms of animal welfare.

The production volume and value estimates which form the basis for commercial value estimates are as follows:

Species	2010	2030	2050
Cod and halibut (tonnes)	22600	30000	50000
Other fish species for human consumption (tonnes)	500	2000	5000
Shellfish , mussels for human consumption (tonnes)	2000	3000	5000
Mussels farmed using IMTA (tonnes)	0	2000	20000
Cleaning fish (million of fish)	12	36	60

Table 6. Estimated production volumes.

New species	2010	2030	2050
Economic value, billion NOK	0.5	1.4	2.5

Table 7. Estimated value of new species for human consumption.

Algae

The term marine algae includes both micro- and macroalgae. Algae obtain energy from sunlight, fix carbon from CO_2 dissolved in seawater and absorb nutrient salts. Algae represent the foundation of the marine food chain:

- Microalgae are unicellular organisms found growing in the oceans' photic zone all over the world.
- Macroalgae are the multicellular plants we know as seaweeds.

Microalgae

Microalgae are the most productive organisms on Earth and are able to increase their biomass two-fold in the space of 24 hours. It is estimated that there are between 200,000 and 800,000 different species of microalgae, of which only 35,000 are described. They exhibit a wide range of properties which make them attractive for exploitation. The exploitation of microalgal biomass on an industrial scale will require the selection of species which exhibit rapid growth and a high content of the useful components. By regulating the conditions of cultivation, it is possible to stimulate growth rates and biomass production, as well as the content of bioactive molecules.

The omega-3 and -6 fatty acids obtained from fish are originally produced by microalgae. In terms of their industrial applications, algae can be used in the production of biomass, bioactive molecules and particular marine lipids, both for human consumption and for fish and animal feedstuffs. The protein fractions have both industrial and medical applications since they contain cold-active enzymes and bioactive peptides (used to reduce blood pressure and in immune modulation).

Macroalgae

Many species of seaweed are found growing naturally along the Norwegian coast, and many have been exploited as food for humans and their domestic animals for centuries. We have established traditions in research into and exploitation of these resources, and the alginate and seaweed meal industries are based on an annual harvest of brown kelp and bladder wrack amounting to about 200,000 tonnes.

A total of 15.8 million tonnes of macroalgae were cultivated globally in 2011 for food, feedstuffs, chemicals, medicines, health foods, cosmetics and fertiliser applications. China, together with the Philippines, Korea and Japan, account for 90% of this production.

Norway possesses both the naturally-occurring conditions and technologies needed to produce much greater volumes than we do today. Our country also possesses high levels of biological expertise as it applies to macroalgae, and is a world leader in the development and operation of aquaculture facilities. In collaboration with other European centres of expertise in macroalgae, we are capable of developing efficient cultivation technologies which can provide us with biomass containing tailored properties which in turn can be exploited as a basis for a wide range of products, both for domestic use and export. Thus macroalgae represent a very interesting raw material for feedstuffs both for farmed fish and domestic farm animals – as a source of protein, functional food (marine oils, fibres etc.) and as the basis of single-cell proteins. They may make a major contribution to future sustainable feed production based on biomass sourced from primary producers. High iodine concentrations may be a cause for concern when using whole seaweeds for the production of feed-

stuffs, and the biomass must be processed in order to reduce iodine content.
Important criteria for economic growth in the microalgae cultivation sector are as follows:

- In the future, the cultivation of microalgae will not necessarily take place in Norway, but rather in countries blessed with more favourable natural advantages such as sunlight, renewable energy sources and nutrient salts. The cultivation companies may very well be Norwegian-owned if the expertise and technologies established in order to achieve cost-effective production have been developed in Norway or as a result of Norwegian funding.
- The generation of know-how in the fields of large-scale production of microalgae.

Important criteria for economic growth in the macroalgae cultivation sector are as follows:

- Large scale production of macroalgae for applications such as bioenergy and feedstuffs.
- Universal acceptance of a further expansion of the areas of coastal waters occupied by mobile facilities and the development of space-efficient cultivation technologies.
- Know-how and technology are developed which enable the full exploitation of harvested biomass (IEA Bioenergy Task, 2012).

The production volume estimates which form the basis for economic value estimates are as follows:

Production of algae	2010	2030	2050
Microalgae, tonnes	0	10000	500000
Macroalgae, million tonnes	0.2	4	20

Table 8. Estimated micro- and macroalgal production.

Price estimates: Macroalgae in 2030: NOK 2 per kilogram
Macroalgae in 2050: NOK 2 per kilogram

Algae	2010	2030	2050
Economic value, billion NOK	1.1	8	40

Table 9. Estimated value of macroalgae production.

Highly productive waters

The term "highly productive waters" is understood to refer to waters in which biological production by means of natural processes or a variety of human interventions can be managed to result in high harvestable yields of commercially attractive plant and animal species.

The world's oceans vary considerably in their potential for harvestable production. Large areas of the open oceans can be regarded as oceanic deserts, whereas coastal waters are often much more productive. Harvestable production is particularly large in the world's so-called coastal "upwelling areas" where large volumes of water containing plant-derived nutrient substances such as nitrates and phosphates rise from deep to shallow levels and form the basis for high rates of production throughout the food chain. This illustrates the potential to increase production in coastal waters by means of aquaculture, since one level down in the trophic chain can represent an eight to ten-fold increase in harvestable production. It has been estimated that up to 50% of harvestable marine production is to be found in upwelling areas, with the remainder occurring primarily in coastal waters at depths of less than 200 metres. This distribution is determined by the degree of natural nutrient input, and reflects particularly the fact that trophic chains are much shorter in upwelling areas.

Japan, China and other Asiatic countries have been exploiting the potential of the oceans for several decades. This is especially true of Japan, where the coastline is cultivated systematically by local communities with harvesting rights. In China, large companies have been awarded time-limited concessions to cultivate the oceans. The Chinese company Zhangzidao Group is currently cultivating a shallow area of ocean located east of Dalian (equivalent to the size of the Norwegian municipality

Oppdal) involving the extensive release of young scallops, sea cucumbers and sea urchins. When the organisms have reached marketable size, harvesting is carried out by divers and re-catch rates are satisfactory (>30%).

Norway has extensive shallow waters which can be exploited in the same way using species such as lobster, scallops and other highly-prized benthic organisms suited to sea-ranching of this type. We have legislation which in principle permits sea ranching, but we have yet to test biological and legislative feasibility by means of specific projects. Since maricultural harvesting requires no feed input, it may become very important if we fail to succeed in developing new feed resources for the aquaculture sector. It will be possible to carry on such activities in areas allocated either to aquaculture and seaweed cultivation or to other commercial activities taking place in coastal waters.

The following initiatives may contribute towards an increase in the harvestable production of desired species:

- Artificial generation of upwelling of deep water, possibly in combination with energy production.
- Habitat restoration measures, such as artificial reefs that generally increase production.
- Advances in breeding technology for relevant species, such as lobsters and large scallops.
- Methods for the release and consolidation of desired species, and predator control.
- Better know-how related to marine production factors with a view to the management of production in shallow oceanic areas.
- ROV (Remotely Operated Vehicle) technologies to enable the monitoring and harvesting of ranched and cultivated organisms in shallow waters.

Research and development work, followed by the launch of commercial maricultural harvesting, must be developed as part of joint international efforts through which Norway can learn from the Asian countries. It is difficult to estimate the value generation potential hidden in the expansion of exploitation from highly productive waters, but it is likely that in 2050 significant and ever-increasing levels of activity will be seen. This is because conditions in our coastal waters are highly favourable. There are some suitable organisms which fetch high prices in the market, combined with a massive interest in the further expansion of our seafood sector. Is it possible that this will become the most important method of producing seafood in the years after 2050? We estimate that the harvested species (lobsters and scallops) will have a commercial value of NOK 50 per kilo.

Highly productive waters	2010	2030	2050
Economic value, billion NOK	0	3	25
Volume, million tonnes	0	0.06	0.5

Table 10. Estimated utilisation of highly productive Norwegian waters.

Conclusion

The 2012 DKNVS and NTVA published report called *"Verdiskaping basert på produktive hav i 2050"* ("Value created from productive oceans in 2050"*)* concludes with the assessment that the potential for value generation in 2050 is divided into two main areas:

- Progressive development of the seafood industry's core areas with which we are currently familiar.
- The development of embryonic and new industries.

Within both of these main areas, separate value chains and areas of focus have been identified which are the key to realising the value generation potential. Some of these can be quantified, while others cannot.

The report outlines perspectives and opportunities which Norway now has, as one of the world's major nations in terms of its economic exploitation of the oceans, in the fields of the cultivation and harvesting of the ocean's biological resources. The report estimates the total values created from productive oceans in 2050 to NOK 550 billion, which is more than six times the value today.

The figure below presents the estimates of value generation potential in the different fields within the marine sector. The estimates have been made on the basis of how development is expected to progress within the fields in question.

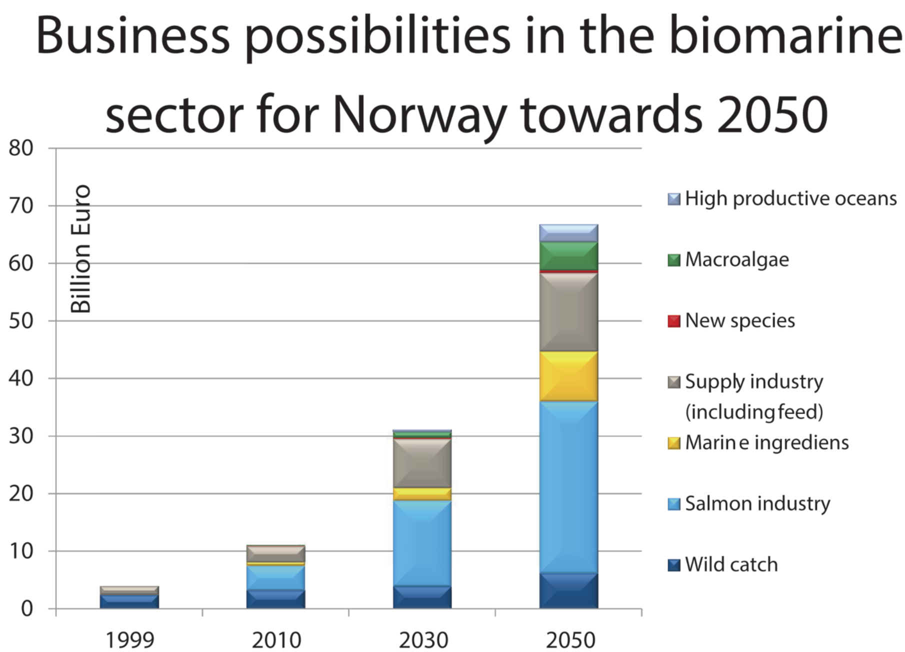

Figure 2. Estimate of total values created (billion Euro) from productive oceans.

The value generation in the marine sector in 2050 is estimated to be a little in excess of NOK 550 billion. In 1999 it was predicted that in 2030 value generation in the marine sector would be just less than NOK 250 billion. This means that the present study is adjusting this potential downwards somewhat in the period leading up to 2030. After 2030 and in the period leading up to 2050 the report expects that global trends such as overall rising demand for food production, and increased demand for seafood in particular, will combine to promote a massive increase in value generation within the Norwegian marine sector and among Norwegian interests overseas.

Other global issues such as climate change and economic instability will conspire to create uncertainty as to whether or not such potential can be realised. A pattern of developments as outlined here will also require for example that the aquaculture industry succeeds in addressing the environmental challenges it faces, thus opening the doors to increased levels of growth. One of the greatest challenges will be linked to obtaining the necessary raw materials for feedstuff production.

References

DKNVS/NTVA (1999). Norges muligheter for verdiskaping innen havbruk. http://www.ntva.no/images/stories/Rapporter/havbruk-1999.pdf

DKNVS/NTVA (2006). Exploitation of Marine Living Resources - Global Opportunities for Norwegian Expertise. http://www.ntva.no/images/stories/Rapporter/biomarine_ressurser-no-2006.pdf

DKNVS/NTVA (2012). Value created from productive oceans in 2050. http://www.ntva.no/images/stories/Rapporter/Value_created_from_productive_oceans_in_2050.pdf

IEA Bioenergy (2012). Task 42 Biorefinery, Bio-based chemicals: Value Added Products from Biorefineries, Report 2012.

Mathiesen, A.M. (2012). Aquaculture towards 2030: Policies for sustainable development. FAO. Presentation given at AquaVision, Stavanger 2012.

Olsen, O.C, Krogstad, N.O., Blakstad, F. and Pedersen, J. (2011). Vekst, lønnsomhet og organisering av leverandørene til havbruksnæringen (Growth, profitability and organisation among suppliers to the aquaculture sector). Notification of Issues to *Teknologi akv*.

Reve, T. and Sasson, A. (2012). Et kunnskapsbasert Norge (A knowledge-based Norway): Published by Universitetsforlaget, Oslo.

Sundby, S. (2012). Effekter av klimaendringer på norske kyst- og havområder. (The effects of climate change on Norwegian coastal waters and

oceans). Norwegian Institute of Marine Research. Presentation given in February 2012. *ARENA*. Prepared by INAQ Management.
Tacon, A.G.J., Hasan, M.R. and Subasinghe, R.P. (2006). Use of Fishery Resources as Feed Inputs for Aquaculture Development: Trends and Policy Implications. FAO Fisheries Circular No. 1018.

Ecological Principles and Options for Seafood Production

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Introduction

Will agriculture be able to supply enough nutritious food for the global human population beyond 2050? This is a question that cannot be avoided given that the population is predicted to reach 9.2 billion by that time (UN 2007, Miller 2008). The growing human population and, primarily, the steady increase in buying power of the global population, drive the demand for a variety of high quality foods. Although fluctuating, increases in food prices over the last decade are evident in international food markets due to the effects of climate change, an increasing trade-off between biofuels and food, and changing patterns of consumption in fast-growing and large developing countries, such as China and India (Conceicao and Mendoza 2009).

The majority of food produced for human consumption is derived from agriculture and, after the food crisis in 2008, there has been growing concern regarding how and if agriculture will be able to sustain greater food demands in the future. In the coming decades, uncertainties exist for the supply of freshwater required for agricultural activities. In particular, freshwater supply is most worrisome in densely populated regions, such as Southeast Asia (Duarte et al. 2009). Other concerns include the availability of phosphate fertilisers and the space needed for such increasing agricultural activities. There are in all events reasonable doubts about our ability to produce the food that will be needed, and this doubt represents in itself a major challenge for society.

With such concerns about the future of agriculture, marine aquaculture may be the most promising future source for food protein since harvesting through fisheries levelled off in the 1990s (FAO 2006). Because a further increase in the supply of freshwater is questionable, future generations will likely need to develop marine aquaculture in a wide sense, and without harming marine ecosystems and marine biodiversity during the cultivation process. The question of obtaining more resources through fisheries is also important. This is theoretically possible, but higher yields will require major changes in how we harvest the oceans today, and these changes involve many political and societal issues.

Intensive marine aquaculture is technologically well developed, but there is a fundamental difference in the developmental stage between agriculture and mariculture. Agriculture technology developed slowly in ancient time, but accelerated quickly in the 20^{th} century (Miller 2008). The production of plants and meat in agriculture has become gradually more and more predictable and controlled. Through access to cheap fertilizers during the so-called *Green Revolution*, farmers could more easily grow the excess plants needed to feed their livestock. As such, the carrying capacity of agriculture increased while the food chain for meat production became well controlled.

In mariculture, there is so far no control of the food chain of cultivated animals. Back in the 1980s, a majority of the feed resources was harvested from the sea, but the current situation is different. The harvesting yields of so-called forage fish are limited to 30–35 million tons per year. During the last 10–15 years, this limitation in available marine resources for feed has been a major driving factor in the gradual substitution of protein and lipid resources of agricultural origin in the feed of carnivorous fish and shrimp, which has enabled growth in the aquaculture industry. Because of nutritional requirements of the fish, there is still a limit on how far that substitution can go (Olsen 2011).

Terrestrial versus marine production

Primary production of plants in the terrestrial and aquatic biospheres is comparable in size (Field et al. 1998). Specifically, carbon assimilation of 50–60 and 40–50 Giga tons of C occurs in the terrestrial and aquatic (marine) biospheres, respectively (Figure 1). Published values exhibit some variation, but the relative distribution between the systems is consistent.

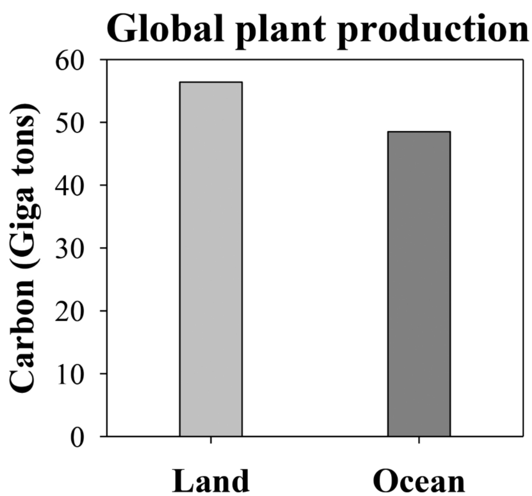

Figure 1. Global plant production in the terrestrial and marine biospheres.

A majority of marine primary production takes place in single cell organisms. Macroalgae, commonly referred to as seaweed, are less important than phytoplankton (microalgae) for global marine primary production. Phytoplankton is highly abundant in bodies of water around the world. Most importantly, it is a readily available food source for grazing animals, such as zooplankton. In coastal waters, molluscs, such as mussels, may also consume phytoplankton. The plant production in the terrestrial biosphere is to a greater extent dominated by larger plant individuals, which partly form indigestible biomass (e.g. wood). These plants are generally less available for animals than the phytoplankton of the sea. Approximately 4–5% of terrestrial plant production is either directly included in the human food chain or available after being upgraded to meat and other products by domesticated animals.

Global agricultural plant production is roughly 8 Giga tons fresh weight per year, whereas the production of meat and other animal products is 0.05–0.8 G tons fresh weight per year as illustrated in Figure 2A (FAO statistics). Plant products accordingly dominate food production in agriculture. Conversely, aquatic food production in fisheries and aquaculture

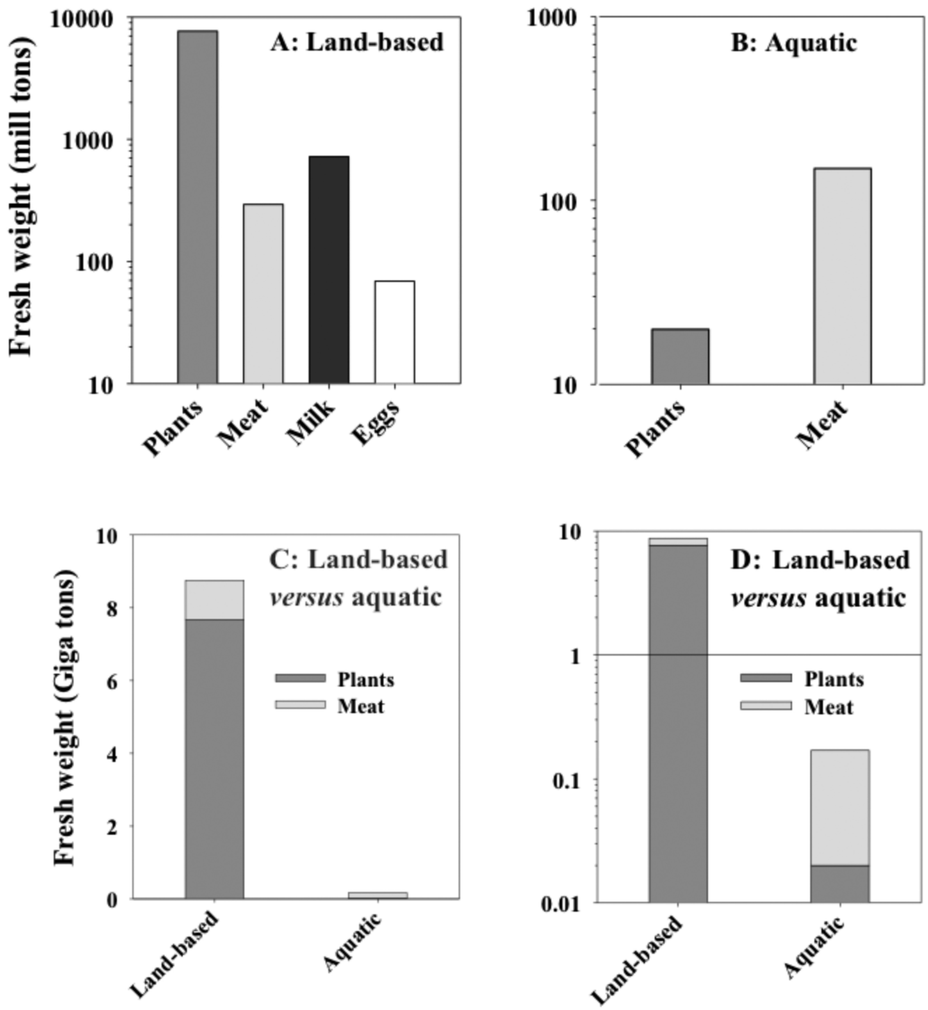

Figure 2. Global land-based and aquatic-based production of food for humans (FAO statistics). A: Main categories of food produced in agriculture, B: Main categories of food produced in fisheries and aquaculture, including freshwater aquaculture, C: Land-based versus aquatic-based food production, D: as C in logarithmic scale. All graphs express fresh weight.

provides 0.02 and 0.15 Giga tons fresh weight of plants and fish meat per year, respectively, including freshwater fish aquaculture (Figure 2B). The production of plants for human consumption in agriculture is accordingly around 400 times higher than in the aquatic environment.

The pronounced differences in terrestrial and aquatic food production are further illustrated in Figures 2C and 2D, showing that agricultural food production is the most prominent while total aquatic food production obtained through aquaculture and fisheries constitutes only 1.9% of total food production (FAO 2006). This observation is counterintuitive given that primary production in the terrestrial and marine biospheres is of similar magnitude based on carbon assimilation (Figure 1). Furthermore, plants in the marine system are more easily available as feed for grazing animals. It therefore appears that the marine production of organisms in the seafood chain is far less efficient than the land-based production. Understanding the principle mechanisms behind these differences in production efficiencies between land-based and aquatic food chains will be instrumental to optimal harvesting of the oceans and successful aquaculture in the future.

Efficiency and yields of food chains

The organisms of both terrestrial and aquatic ecosystems form food chains, also referred to as food webs, through which organic matter and energy are transferred from plants to plant-eating animals (denoted grazers or herbivores), then to animals that eat other animals (termed carnivores). Figure 3 illustrates a simplified marine food chain for organisms that live in the water masses (pelagic organisms). Phytoplankton comprises the lowest level of the food chain (termed trophic level 1). Animals that feed on phytoplankton are mainly microscopic zooplankton of various sizes that use a special filtering process to isolate and take up the phytoplankton. Molluscs may also consume phytoplankton, but their overall contribution in the harvesting of marine plants is minor compared to that of the zooplankton. Nevertheless, together they form the second level of the food chain (denoted trophic level 2). Large zooplankton feeding on trophic level 2, such as herbivore copepods and krill, are the primary food source for

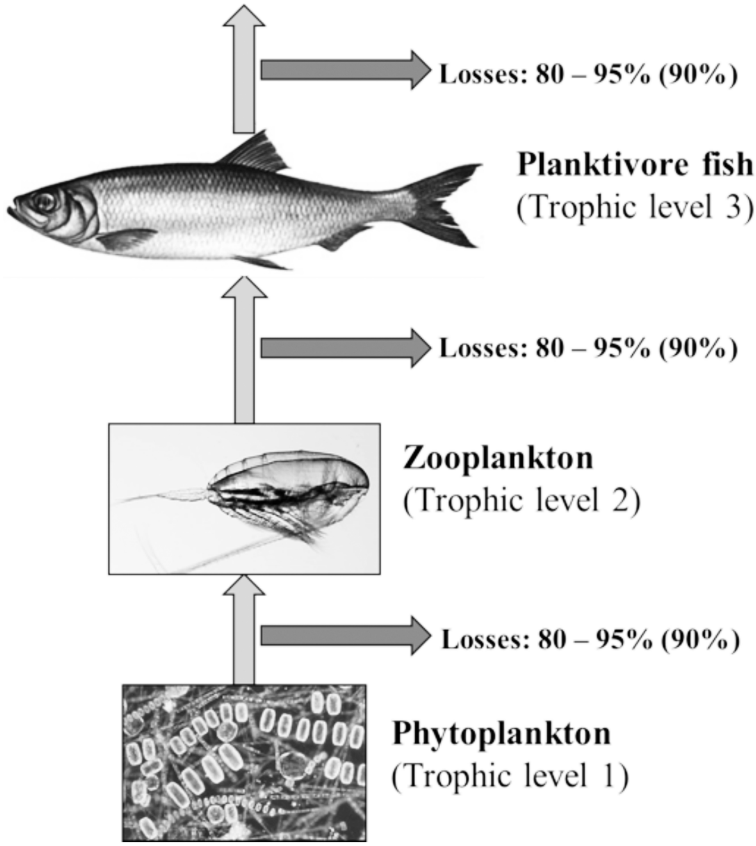

Figure 3. Schematic three-step marine food chain.

many fish species like herring, capelin, sardines and carnivore zooplankton species such as jellyfish, which together form the third level of the food chain (trophic level 3). Other fish species, such as cod, may feed on these fishes and are therefore on trophic level 4.

All animals need energy to maintain their metabolism and growth, resulting in energy and carbon losses in the form of CO_2 (~40–60% of eaten C in food). Moreover, a significant fraction of their food is not digestible, resulting in losses of organic carbon through defecation (~25–35% of C in eaten food). Some individuals will also die and, thereby, contribute to carbon losses in the food chain. In total, 80–95% (mean 90%) of the energy/carbon consumed by an animal is lost back into the environment as CO_2 and organic components. The result of these losses is that only 5–20% of the consumed food (mean 10%) is incorporated in biomass at the next trophic level. The overall values are mostly empirically determined, as in the classical work of John Ryther (Ryther 1969). Direct measurements of respiration and defecation rates made frequently over the last decades have revealed that the empirical values of early marine scientists are representative, but approximate only (Olsen et al. 2007).

The above principle of energy and carbon loss in food chains is universal, whereby the concept virtually expresses a biological law of nature, similar to the laws of thermodynamics. It can explain a primary mechanism behind the low efficiency of the marine production process of organisms that are high in the food chain. While often described in marine ecology and oceanography textbooks, the impacts and the obvious consequences for production efficiency are not always considered. The exact values for losses following one or more trophic transfers are unknown, but the overall effect will always be that carbon and energy are rapidly lost in a food chain of considerable length. In the three-level food chain illustrated in Figure 3, overall losses may be 96–99.8% (mean 99%), so that just 1% of the phytoplankton carbon eaten is accumulated in biomass on the third trophic level (Table 1). The overall yield for a four-level food chain is in the order of 0.1% of primary production.

Trophic level	**# Trophic transfers**	**Specific trophic transfers**	**% yield of primary production**	**% yield (min – max)**
1	0	CO_2/nutrients to phytoplankton	100	100
2	1	Phytoplankton to zooplankton	10	5 - 20
3	2	Phytoplankton to planktivore fish	1	0.25 - 4
4	3	Phytoplankton to carnivore fish	0.1	0.013 - 0.8

Table 1. Typical values of energy and carbon transfer efficiencies through a marine food chain of four trophic levels. Values are related to the primary production of trophic level 1, the marine primary production.

The physiological mechanism of energy and carbon losses in marine food chains is accordingly well understood, but the mechanism will work also in terrestrial food chains. Warm-blooded mammals tend to have even higher metabolic losses than cold-blooded aquatic animals. However, the *human seafood chain* is more extensive, it involves several more trophic levels than the human *agriculture food chain*. As a result, seafood production is far less efficient than agricultural food production.

Figure 4 provides a schematic illustration of the human food chains for seafood and agricultural food. Virtually all food items in agriculture originate from trophic levels 1 and 2. Carnivores at trophic level 3, such as wolves and wolverines, are not utilised as human food. Higher carnivores, e.g. animals that eat wolves or animals that eat wolf-eaters in trophic levels 4 and 5 remain largely unknown, and are in any event an insignificant fraction of human food. The trophic level of humans will vary from position 2 for vegetarians to level 3 for obligate meat eaters. If an agriculture-based diet constitutes 20% meat and 80% plants, the human trophic level will be 2.2.

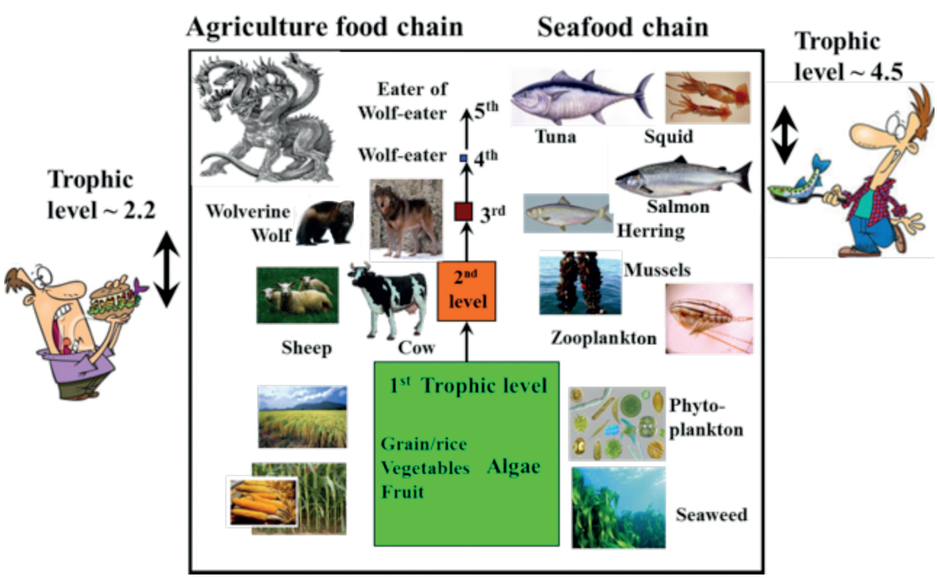

Figure 4. Schematic view of the human food chains for agricultural food and seafood, with indications of the human trophic level for the two food chains

Members of trophic levels 3 and 4, such as herring and cod, respectively, are common items of the seafood chain of humans (Figure 4). Items of the lower levels (e.g. mussels and macroalgae) as well as trophic level 5 (e.g. tuna and certain squids) are, to some extent, consumed by humans, but these items are not that quantitatively important as food. If the seafood diet constitutes 50% meat from trophic level 3 and 50% from trophic level 4, the human trophic level for such seafood will be 4.5. This implies that only 0.1–0.01 % of the initial marine primary production of the phytoplankton is retained in the seafood.

Figure 4 suggests that humans generally feed >2 steps higher in the seafood chain than in the agricultural food chain. As this implies more than two extra trophic transfers in the seafood chain, there is 99% *extra* loss in the seafood chain compared to the agricultural food chain. If all other factors are equal, this suggests that marine seafood production should be <1% of terrestrial food production, and this value fits quite well with the real values for food production shown in Figure 2. This suggests that the exponential process of loss during trophic transfers is the strongest process in calculating final production yields.

There are, however, many modifying factors. As mentioned above, the agricultural food chain constitutes some 4–5 % of total terrestrial primary production. The primary production of the marine ecosystem is more directly available for grazing animals and the higher food chain (Figure 5), but there are major losses of seafood resources through the feeding and growth of seabirds and marine mammals. Moreover, the estimated seafood production in Figure 2 includes freshwater fish (~30 million tons). Taken together, estimates that 1.9% of our available food is produced in the aquatic environment are consistent with the simple analysis of energy conversions and food chain structures.

Figure 5. Examples of terrestrial and marine plants, of which microscopic phytoplankton dominate in terms of biomass.

General strategies for fisheries and mariculture

The key point from the above discussion is that most of the primary production of the oceans is lost because humans mainly harvest and eat organisms high in the marine food chain. The obvious action to reduce losses would then be to also harvest and culture organisms lower in the food web. The elements of a general strategy may be:

- **For fisheries, also harvest members low in the food chain**
  - Large zooplankton (e.g. Antarctic krill and red feed).
  - More seaweeds, for feed and human food.
- **For mariculture, produce more organisms low in the food chain**
  - Seaweeds, for human food and feed, the global production is already growing fast.
  - Molluscs, feed on phytoplankton and wastes.
  - Other low food-chain organisms.
- **For mariculture, move farmed carnivore fish down in the food chain**
  - Use more plants and micro-organisms for feed.

Herbivore zooplankton feed one level below their predators, the planktivore fish, in the food chain (Figure 3), and the world's oceans have two well-known large stocks of herbivore zooplankton; Antarctic krill and red feed. Antarctic krill (*Euphausia superba*) has a standing stock biomass estimated of approximately 500 million tons, estimates ranging from 125–750 million tons (Nicol and Endo 1997). As the lifespan is around 6 years, an annual production of at least 100 million tons per year is likely. The calanoid copepod *Calanus finmarchicus,* or red feed, is abundant in Nordic Seas and has an estimated production in the range of 74 million tons per year (Aksnes and Blindheim 1996), and on-going research continues to characterise the suitability of this species as a resource for human food or cultivated fish (Olsen 2011). Both stocks exhibit an annual production comparable to global catches of fish and squid, which is around 80–90 million tons per year (FAO 2006).

There is a great potential for harvesting and farming more seaweed and molluscs, which feed low in the food chain, and the global production in mariculture of both these groups of organisms is increasing faster than for fish and crustaceans. Based on Chinese experience in farming kelp species, the area needed for producing seaweed in amounts comparable to total global plant production in agriculture (Figure 2) can be estimated to be around 1% of the surface of the global ocean.

For a salmon-producing country such as Norway, there is a particular need to establish new bioresources of food for aquaculture. A general strategy may be to move the salmon to a lower trophic level in the seafood chain. This will not require genetic or metabolic manipulations, but simply formulation of an efficient carnivore feed based mostly on ingredients from plants and micro-organisms. This will reduce the use and loss of primary production, whether land- or marine-based. Another consideration about future feed resources is that they should not also be main components of the human food chain. Moreover, if most resources are also obtained from the sea, the aquaculture food chain can be self-sufficient with little interaction with the human food chain. Some potential bioresource options for feed are:

- Farmed seaweed, perhaps the most important bulk resource of proteins; sugars from the seaweed can be used to produce biofuel.
- Single cell biomass, based on micro-organisms including microalgae, perhaps the most important sources of lipids of marine quality.
- Other suitable wasted food resources from agriculture.

The challenge of preparing feeds for carnivore fish using plant ingredients and micro-organisms is not trivial. A nutritionally adequate feed for fish must contain sufficient amounts of marine lipids with long-chain, highly unsaturated fatty acids, such as DHA (22:6 n-3), which are only abundant in aquatic food chains (Olsen 2011). The establishment of new and nutritionally adequate feed resources taken from a low trophic level is, therefore, a great challenge for science, industry and society.

Implementation of the general strategy

The efforts to move the cultivated fish to a lower trophic level in the seafood chain have already been ongoing for at least 10–15 years. Marine products in feed have gradually been replaced with increasing fractions of plant products produced in agriculture. This change was made possible through implementation of comprehensive European research projects (e.g. AQUAMAX project, http://www.aquamaxip.eu), and has been driven by limited availability and increasing prices of fish oil and fishmeal. During this process, cultivated fish have been moved gradually to a lower trophic level in the seafood chain as plant products have essentially replaced marine animal products in the feed (Kaushik and Troell 2010).

Figure 6 exemplifies this development together with a future prediction for Norwegian salmon farming. In 1980, the salmon feed was entirely prepared from marine products produced from forage fish feeding on trophic level 3 (Figure 3). All feed resources were then entirely dependent on marine primary production, and the salmon fed at trophic level 4, which

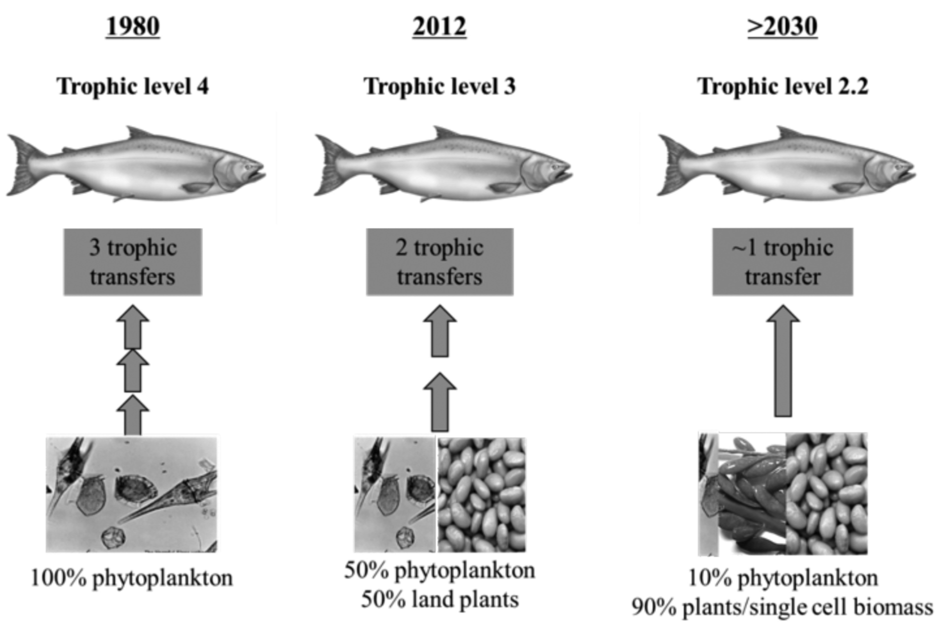

Figure 6. Feed ingredients and trophic structure of the food chain for salmon farming from past, present, and for the future.

requires three trophic transfers. This means that less than 0.8% of the underlying marine primary production, the main scarcity factor, was finally incorporated into the salmon (Table 1). In 2012, salmon feed was prepared using approximately equal fractions of marine and agricultural plant resources. The salmon farmed in 2012 then used half the amount of marine primary production compared to the salmon farmed in 1980, then feeding on trophic level 3 (2 trophic transfers).

It is not known what fish feed will be comprised of beyond 2030. If we assume that marine animal products constitute 10% of the feed while the remaining 90% is made up of marine and agricultural plant products and biomass from micro-organisms (Figure 6), the salmon will use approximately 10% of the limiting marine primary production as compared to 1980. This salmon would feed on trophic level 2.2, which is close to that of plant-eating animals in aquaculture and agriculture.

Efficiency of feed utilisation

The production yields (fish produced per unit feed consumed) of salmon fed with pelleted feed is much higher than the 10% which is the empirical value usually used for natural food chains (Figure 3, Table 1). In modern salmon aquaculture, around 40% of the energy and proteins in the feed is incorporated into the salmon meat. This means that the values in Table 1 underestimate the salmon yields, at least for 2012 and later. Figure 7 illustrates this by comparing wild and cultured salmon. Farmed salmon today consume 50% of marine resources compared to the wild salmon. In addition, the production yields are 40% and likely much higher than for wild salmon stocks. If the above-mentioned assumption about food conversion efficiency of the wild salmon of 10% is realistic, it implies that we get 8-times more salmon per unit of marine primary production used for farmed salmon than wild salmon. This high production yield of farmed salmon, in combination with the use of the assumed plant/micro-organism dominated diet beyond 2030 (Figure 6), will make salmon as efficient in production as agricultural animals in terms of meat produced per unit primary production invested.

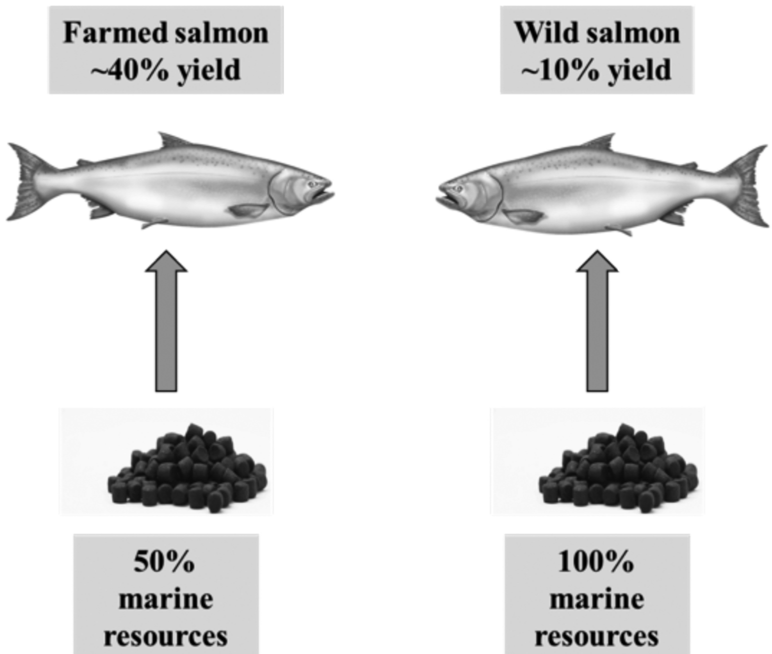

Figure 7. Comparison of feed ingredients and feed utilisation efficiency of farmed and wild salmon.

Concluding remarks

The scenario described for increasing the efficiency of seafood production represents major challenges for policy makers, management, science and the private sector. There will doubtless be lots of environmental, social, economic and ethical questions that need to be addressed along the way, while short cuts in the suggested, strategic roadmap may become apparent, for example as a consequence of new knowledge and new genomic technologies. Science has a particular role and responsibility to explore possibilities, constraints and consequences of the upcoming issues in an open-minded and transparent way.

References

Aksnes, D.L. and Blindheim, J. (1996). Circulation patterns in the North Atlantic and possible impact on population dynamics of *Calanus finmarchicus*. Ophelia 44, 7-28.

Conceicao, P. and Mendoza, R.U. (2009). Anatomy of the global food crisis. Third World Quarterly 30, 1159-1182.

DKNVS-NTVA (2012). Value Created from Productive Oceans in 2050. A report prepared by a working group appointed by the Royal Norwegian Society of Sciences and Letters (DKNVS) and the Norwegian Academy of Technological Sciences (NTVA), pp. 83. (http://www.ntva.no)

Duarte, C.M., Holmer, M., Olsen, Y., Marba, N., Guiu, J., Black, K. and Karakassis, I. (2009). Will the oceans help feed humanity? BioScience 29, 967- 976.

[FAO] Food and Agriculture Organization (2006). The State of World Aquaculture. FAO Fisheries Technical Paper 500. (http://www.fao.org/docrep/009/a0874e/a0874e00.htm)

Field, C.B., Behrenfeld, M.J., Randerson, J.T. and Falkowski, P. (1998). Primary production of the biosphere: Integrating terrestrial and oceanic components. Science 281, 237-240.

Kaushik, S.J. and Troell, M. (2010). Taking the fish-in fish-out ratio a step further. Aquaculture Europe 35, 15-17.

Miller, F.P. (2008). After 10,000 years of agriculture, whither agronomy? Agronomy Journal 100, 22-34.

Nicol, S. and Endo, Y. (1997). Krill fisheries of the world. FAO Fisheries Technical Paper 367.

Olsen ,Y., Andersen, T., Gismervik, I. and Vadstein, O. (2007). Protozoan and metazoan zooplankton-mediated carbon flows in nutrient-enriched coastal planktonic communities. Marine Ecology Progress Series 331, 67-83.

Olsen, Y. (2011). Resources for fish feed in future mariculture. Aquaculture Environment Interactions 1, 187-200.

Ryther, J.H. (1969). Photosynthesis and fish production in the sea. Science 166, 72-76.

United Nations (2007). World Population Prospects: The 2006 Revision Population Database (31 January 2010; esa.un.org/unpubl).