The Digital Salmon – Key to both More Science and More Profit

Stig W. Omholt
Professor, Faculty of Medicine, Norwegian University of Science and Technology, stig.omholt@ntnu.no
Arne B. Gjuvsland
Researcher, Centre for Integrative Genetics, Norwegian University of Life Sciences, arne.gjuvsland@umb.no
Jon Olav Vik
Researcher, Centre for Integrative Genetics, Norwegian University of Life Sciences, jonovik@gmail.com

Introduction

Norway has been a prime contributor to the development of today's knowledge base for aquaculture-related salmon biology, and this knowledge base has been essential to the industrial success of Norwegian salmon farming. Genomic information is a key premise for advanced biological research and development, and Norway is now playing a major role in the international collaboration to sequence the Atlantic salmon genome. However, access to a high-quality genome sequence is only a first step towards establishing a sorely needed quantitative and widely applicable knowledge base for one of Norway's most important export articles. The construction of such an intellectual edifice exposes us to the most daunting challenge facing modern biology, namely how to build a causal bridge between the genome, environmental influences, and the phenome (the totality of an individual's measureable traits). In line with current international trends within biomedicine and production biology, we argue that the only feasible way to establish such a knowledge base is to aim for the construction of a Digital Salmon – a comprehensive, computer-encoded representation of our growing knowledge of salmon biology.

Patterned on similar endeavours in human biomedicine, a Digital Salmon would encompass an ensemble of mathematical descriptions of salmon physiology, combining mathematics, high-dimensional data analysis, computer science and highly advanced measurement technology with genomics and experimental biology into a concerted whole. The development of such a quantitative framework by merging life sciences, mathematical sciences and engineering would be highly instrumental in adapting salmon to new and sustainable feeds without sacrificing product quality, in understanding complex diseases and developing new vaccines, and in preserving wild salmon populations. In addition, it would contribute strongly to the visibility of Norwegian biological research at the international research frontier while providing the foundation for a new biotechnological industry.

It takes all the running you can do to keep in the same place: The future of salmon research and development in Norway

The Red Queen is a fictional character in *Through the Looking-Glass* (Carroll, 1871), the sequel to *Alice's Adventures in Wonderland.* Having led Alice to the top of a hill, the Red Queen begins to run, faster and faster. Alice runs after, but is baffled to find that neither one seems to be moving. Alice remarks on this, to which the Red Queen responds: "Now, *here*, you see, it takes all the running *you* can do to keep in the same place". This is an apt metaphor for what it takes to sustain a long-lasting and profitable Norwegian salmon industry.

To maintain production volumes, not to mention move forward, this industry has to continuously deal with and adapt to a range of biological and non-biological challenges that make up a demanding Darwinian theatre where the possibility of severe decimation, or even extinction, always lurks behind the scene. The salmon industry stands out among

Norwegian knowledge-driven export industries by having only a rudimentary understanding of how its product is designed and how to adjust this design to the demands of production or market conditions. This is due to the fact that the product is a highly complex organism, kept in an uncontrolled environment (the sea), where major biogenic production factors (feedstuffs) must be acquired from highly competitive markets. Furthermore, even though the industry has successfully dealt with several of the challenges it has been exposed to during its 40 years' history, the predicament laid out by Red Queen is unavoidable. Therefore, there is a need to actively acquire and utilize a deep knowledge of salmon biology; a need that will become more and more prominent as the industry expands.

Recently, the Norwegian academies of science commissioned a report titled *Value created from productive oceans in 2050*. Looking forty years into the future, the authors foresee that "In 2050 biotechnological and genetic methods have enabled the development of a sterile salmon with excellent growth properties and robust immune system" (Olafsen *et al.*, 2012 p.44). Without debating the merits of this goal, we acknowledge that a sterile salmon is within reach long before 2050. However, the claim that biotechnological and genetic methods have enabled the development of a salmon with excellent growth properties and robust immune system, is arguably not paying enough attention to what is conveyed by the above Red Queen metaphor. In this chapter, we address what it takes to develop and maintain a salmon with excellent growth properties and a robust immune system while the estimated annual production increases from the current 1 million tons/year to a prospected 5 million tons/year in 2050 (Olafsen *et al.*, 2012). Our major claim is that this goal is not likely to be achieved in a sustainable way unless we take Norwegian research and development on salmon biology to a completely new level along several theoretical, experimental, technological and organisational axes.

The need for a systems understanding of salmon biology

Norway is at the fore of the international collaboration to sequence the genome of the Atlantic salmon, thanks to co-operation between Norwegian research groups, the industry and the Research Council. Genomic information is a key premise for advanced biological research and development, and the salmon genome is expected to yield unique knowledge of relevance to great current challenges in aquaculture as well as the management of wild salmon. In fact, DNA information is used in at least four types of application in biology (Gjuvsland *et al.*, 2013):

- As a **pure marker** of phylogenetic origin and history, without reference to any particular phenotype (i.e. observable trait of interest). Examples include quantifying genetic divergence between salmon stocks from different rivers, identifying escaped farmed salmon, studying selection history and effective population size, and describing genome structure.
- To detect **statistical association** between variation in DNA and in phenotypes. Salmon phenotypes currently being targeted are for example growth rate, colour, fatty acid composition, the ability to utilize different feeds, and resistance to disease agents.
- To document the existence of a **causal connection** between a particular DNA variation (natural or imposed) and variation in a specific phenotype**.** For example, many single-nucleotide polymorphisms (SNPs, i.e. point mutations) may all be correlated with a given phenotype, but only a few may have a causal effect.
- To account in a **causally cohesive** way for the genome-phenome relationship in terms of biophysical mechanism at the cell, tissue and organ system levels under various environmental conditions and life stages. We will specify what this means by defining some key concepts. The term *system* denotes a set of interacting and interdependent components that form a unified whole. In particular, living beings are *dynamical* systems: their state changes over time due to the physiological processes of its component cells, tissues and organs. The adjective “cohesive” means “causing to cohere” (Merriam-Webster, 2008), and Rajasingh et al. (2008) defined a causally cohesive genotype-phenotype model as one that, at some given level of resolution, has the quality of causing components

> involved in a genotype–phenotype relation to cohere in a logically consistent and ordered way. This is in contrast to standard population genetic models, where phenotypic values are assigned directly to genotypes without involving any intermediate processes.
>
> Thus, fish are dynamical systems in that physiological processes change the state of the body, and the rates of the various processes depend on the body state and external influences. These dependencies may vary for both genetic and environmental reasons. Odd Arild Olsen's Dr. Ing. thesis at the Norwegian Technical University more than 20 years ago, titled *Structured modelling of fish physiology*, represents a truly pioneering contribution in this direction (Olsen, 1989).

Using statistical associations, Norwegian breeding programmes for salmon are now successfully selecting individuals resistant to IPN (infectious pancreatic necrosis) even before the full salmon genome is available (Anon, 2010). A few research groups have also already embarked on the much more challenging task to identify the specific causal genetic variation underlying important traits. Even though these two approaches are likely to be sufficient for tackling several important issues in the years to come, it should be kept in mind that their usefulness depends on the availability of existing genetic variation in the salmon population. Due to this they provide only a very narrow window of insight concerning the genome-phenome relationship as such, an insight that is needed for establishing a really pre-emptive knowledge base providing comprehensive explanatory and predictive capability. Only a causally cohesive understanding can meet this need, and this is what a Digital Salmon will provide.

The genome-phenome relation is the outcome of very complex dynamics that are also heavily influenced by the environment. It cannot be overemphasised that there is no direct causal arrow from genotype to phenotype in the sense that DNA is responsible for exerting a direct effect as *a sub-system* on the system dynamics. The causality flows from the physiological state of the organism through a *change in use* of DNA, which in turn influences the physiological (or systems) state. In those cases where variations in DNA cause changes in the system dynamics, it may lead to detectable physiological variation (Omholt, 2012). This way of perceiving the function of DNA in a genome-phenome context brings quantitative physiology back as the major arena for understanding organisms.

The standard definition of physiology is "the study of the functions and activities of living matter (as of organs, tissues, or cells) as such and of the physical and chemical phenomena involved" (Gove, 1981). Thus it is a discipline that per definition seeks integrative understanding of the body as a *system*. Such understanding is exactly what we need if we are to change the fact that one of Norway's largest export industries has only a rudimentary understanding of its product. And it will not be obtained unless we start making use of the vocabulary designed for describing and analysing dynamical systems, namely mathematical modelling. Biological systems are just too complex to be understood in systemic terms by the simple conceptual models still used by most biologists. Despite their usefulness, the same is true for the sophisticated statistical models and bioinformatics tools currently being employed to extract understanding from the huge –omics data sets that are accumulating at an increasing rate. (The suffix -omics is used in biology to form nouns meaning a study of the totality of something, e.g. genomics, proteomics; Wiktionary, 2013.)

The efficacy of computational models in physiology arises from their capacity to connect a comprehensive amount of empirical data into a functional whole:

- By enforcing explicit formulations of various hypotheses.
- By precisely framing the quantitative consequences (prediction space) of hypotheses, by initiating and canalizing experimental or empirical work by pointing out key questions and the type of data needed.
- And last but not least, by providing a very efficient interface for communication between a whole range of disciplines with only partly overlapping vocabularies, helping to integrate the intellectual capital of these disciplines.

These are the rationales for the large investments now being made worldwide to mathematize biological research.

Two of the most important long-term requirements for the salmon industry are the following. (i) It needs to be able to compose a low-cost diet of sustainable food items, obtained from a highly dynamic global market, that does not compromise the salmon's physiology. (ii) It needs to understand the disease physiology of salmon associated with pathogens and parasites so well that when a new epidemic arises, one will, if biologically possible, be able to fast and efficiently remedy the situation and give the salmon a long-term competitive edge. It is wishful thinking to assume that this will be achieved without the massive involvement of advanced mathematics, high-dimensional data analysis, computer science and new advanced measurement technology. Such an endeavour will be outlined in the following sections.

The Norwegian salmon production industry qualifies as a *biotechnological* industry under the definition used by the OECD and Norwegian authorities: "The application of science and technology to living organisms as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services" (OECD, 2005). A merging of life sciences, mathematical sciences and engineering to develop a transformative knowledge base for the Norwegian salmon industry concords with major trends in international biotechnological research and development. In the following we outline international developments on establishing mathematically phrased and biophysically based understanding of human physiology and illustrate how Norway can piggyback on this development to make its own stamp at the international fore through a vision-based and pre-emptive R&D biotechnology programme aiming for a Digital Salmon.

Piggybacking on the Virtual Physiological Human

The Virtual Physiological Human (VPH) is a pan-European effort that aims to "revolutionize twenty-first century bioscience by fundamentally shifting the basis for the diagnosis and treatment of disease" by "biophysically based computational modelling of the human body and physiology" (Hunter *et al.*, 2013). Solid EU funding under FP7 is a recognition that specialisation in medicine is reaching its limits with regards to drug discovery, health budgets and identifying the treatment that best fits each patient. The vision of the VPH is therefore that "Medical innovation should … be directed towards optimizing treatments using … a customized computer model of the patient's condition across multiple organ systems and length scales, and across time and environment" (Hunter *et al.*, 2013). Developing this Digital Patient will involve both the doctors that deal directly with patients, applied research on populations, development of new drugs, and basic research on physiological understanding and mathematical modelling.

The VPH builds on the worldwide Physiome Project, and its framework for modelling the human body using biochemical, biophysical and anatomical information on cells, tissues and organs (Hunter & Borg, 2003, www.physiomeproject.org; see Figure 1). Each organ has its subproject, describing for example gas flow in the lungs, mechanics for the skeleton, electrophysiology for signal propagation in the heart and nervous system, soft-tissue mechanics for muscle contraction, and biochemistry for metabolism. A major challenge is that a functioning organ relies on an interplay between fast and slow processes on micro, meso and macro scales. Hence, submodels are developed to describe processes on different levels of organization from single cells to tissues to the whole organ, and these submodels are coupled and integrated into multi-scale and multi-physics models. The Digital Patient reflects a current push to represent variation between individuals. Some challenges are only beginning to be handled, such as the organism-level interplay of organs, how environment modifies the genotype-phenotype relation, and the robustness and plasticity of bodily development.

Figure 1. The Physiome challenge: From organs to proteins across enormous scale differences in time and space. Figure courtesy of Peter J. Hunter.


Environment
Organism
Organ system
Organ
Heart
Lungs
Diaphragm
Knee
Colon
Liver
Eye
x 1million
20 generations
Tissue
Cardiac sheets
Acinus
Osteon
Lymph node
Liver lobule
Nephron
Cell
Network
Protein
Gene
Atom

The Physiome Project represents an unprecedented scaling up of the use of mathematical modelling to consolidate and integrate physiological knowledge, a wide array of observable quantities throughout the phenotypic hierarchy and physical laws and principles, into comprehensive structure-function representations of cells, tissues and organs**.** This advanced engineering approach makes use of some of the most cutting-edge technology and theoretical constructions currently available. Models of this kind provide an ideal framework for exposing our understanding of how the body works to confrontation with high-resolution biological data.

The Physiome Project has developed a strong infrastructure to integrate the data and knowledge needed (Figure 2). Model repositories store mathematical models in a format that allows both mathematical analysis, autogeneration of computer code, and precise labelling of the components of the model. This labelling uses standardised vocabularies for biological knowledge, making it easy to find models for a particular phenomenon or data to validate a given model. Researchers can ask *biologically meaningful questions* that get translated to machine-processing of enormous amounts of data, including databases of genome sequences, gene expression and protein function.

Model markup languages such as CellML and SBML are used to encode mathematical models, similar to how HTML encodes webpages. They have made it much easier to check, share and reuse mathematical models. This is essential for testing and refinement, especially in integrative work such as virtual physiology. Moreover, a common language makes a model usable with software for many different purposes: human-friendly formatting, automatic checking that units match up on both sides of an equation, mathematical analysis, or generation of computer code for numerical simulation. This is a huge improvement from the slow, error-prone process of coding models from scratch based on a textual publication.

Model repositories are databases of mathematical models in a standard coding. Models are *curated* to verify that they reproduce results from the paper in which they were published, and to ensure standardized labelling of model components, variables and parameters. The major

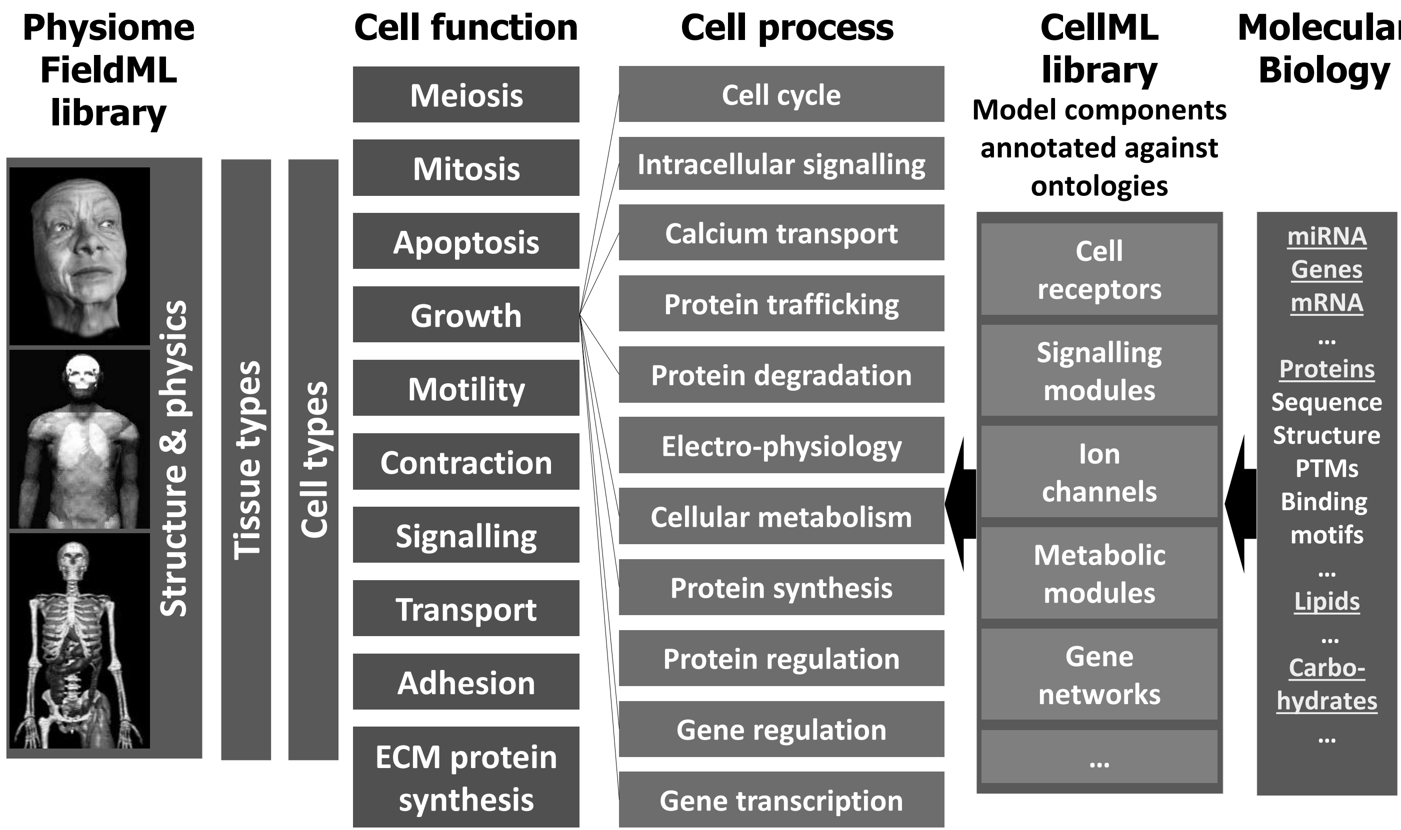


Figure 2. Infrastructure for linking molecular biology to physiome. Figure courtesy of Peter J. Hunter.

repositories today (biomodels.net and cellml.org) have a few hundred models each, mostly for differential equation models of cell biology such as metabolic networks or cellular electrophysiology. This is likely to expand fast in the near future, both in the number of models and the breadth of biological processes and mathematical frameworks, through projects such as Drug Disease Model Resources (ddmore.eu).

Ontologies. The vast knowledge embodied in genomic and phenomic databases and model repositories can only be used effectively together if data and models are properly labelled, allowing data and model resources to speak the same language. This requires formal representations of knowledge, called *ontologies*, which are lists that uniquely identify concepts and the relations between them within a specific domain (de Bono *et al.*, 2011). Thus, labels such as "abnormal enlargement of liver cells" can be given a precise technical meaning, allowing consistent exploration and querying of multiple data and model resources by bioinformatics means. Even data that is private (patient details, intellectual property or preliminary work) can be publicly labelled, thus making potential users aware that such data exist, after which access can be negotiated. Such labelling and cross-referencing is already in place for many -omics databases, whereas for model repositories it has just started. Ontologies exist for anatomy, medical terms, gene function, protein structure, and so on. The BioPortal at bioontology.org gives a human-friendly overview (Noy *et al.*, 2009).

Phenomics denotes the systematic, massive measurement of phenotypes such as gene expression, metabolic activity, anatomic structure from the subcellular to the whole body, and response to diagnostic stimuli (Lanktree *et al.*, 2010; Houle *et al.*, 2010). This is still rare and mostly limited to model organisms such as fruit flies or mice (Houle *et al.*, 2010), but will need to become routine to realise the ambitions of physiome research and human medicine (Gurwitz, 2012; Hunter *et al.*, 2013). Furthermore, phenomics must go hand in hand with modelling, both to prioritise what to measure and to meet the main challenge of -omics research, namely that of integration and meaning (Joyce & Palsson, 2006). This poses challenges and opportunities for research funding and industrial innovation alike (Hunter *et al.*, 2013).

Scurrying in the footsteps of the Virtual Physiological Human comes the Virtual Physiological Rat (Beard *et al.*, 2012), a large systems medicine project linking genetics to models of the cardiovascular system. Similar efforts for the mouse (Land *et al.*, 2013) and other model organisms are underway; for instance, the zebrafish has become an important model organism for disease and the immune system (Lieschke & Currie, 2007; Weinstein *et al.*, 2009).

The Digital Salmon

A flexible basis of knowledge is necessary for rapid response to shifting circumstances in aquaculture. When a new challenge arises, we must be able to easily reanalyse our existing information and understanding of salmon biology. If information is found to be lacking, we must be able to rapidly acquire new data and incorporate it straight away into a unified whole. To deal with upcoming issues in combating disease or adapting feed composition while ensuring product quality, we need to understand the interplay between physiological processes (including the effects of genetic variation), the state of the body, and external factors such as feeding, pathogens and temperature. In this way, we shift from a *reactive* to a *pre-emptive* R&D strategy.

A ***Digital Salmon*** would encompass a coherent digital and mathematical representation of the salmon body, which can be adjusted to represent individuals with different genetic make-ups, populations, disease states, feeding regimes, or other scenarios of interest. Pragmatically, it will mean a suite of computer models for specific purposes, with different simplifying assumptions and levels of detail. Crucially, these models will be linked to databases of biological knowledge, using human-friendly systems for biologically meaningful queries across many data sources at once. Tailored user interfaces will serve different user groups in academia, the institute sector and industry and different activities (e.g. developing or refining mathematical models, using established models for management decisions and experimental design).

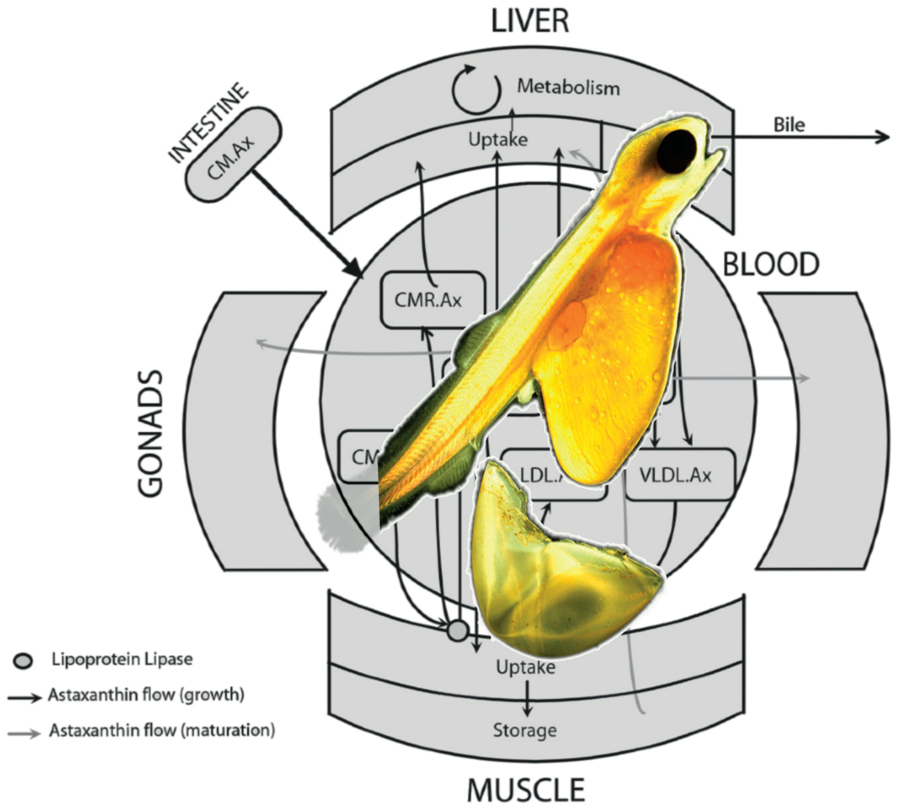


Figure 3. The Digital Salmon is a vision of a coherent digital and mathematical representation of the salmon body, its organs, processes and functions. Piggybacking on similar efforts in human biomedicine, a Digital Salmon would bring together vast amounts of physiological knowledge in a quantitative, predictive whole. Such a knowledge structure would make for much more rapid and flexible responses of salmon farming to novel challenges and shifting demands in disease, feed availability and pricing. The diagram illustrates salmon meat redness (a commercially important phenotype) from a systems point of view. The red pigment astaxanthin (an expensive component of the feed) is taken up from the intestine, transported in blood and deposited in muscle, skin and other organs. The rates of these processes depend on the body state (e.g. sexual maturation: grey vs. black flux arrows) and external influences (e.g. diet composition). Rajasingh et al. built a biophysically based mathematical model to mimic pigment uptake and retention over short and long time periods (hours, days and years) for various feed experiments, shedding light on individual variation in pigment utilisation and meat colour. (See Acknowledgements for image credits.)

The integration of physiological knowledge in a Digital Salmon would address many of the challenges identified in the introduction. It would serve as a common framework and intellectual meeting place for a wide array of various competences in a similar manner to the Virtual Physiological Human. Most of these competences in life sciences, mathematical sciences and engineering are currently not involved in research on fish physiology, disease, nutrition and product quality. We strongly believe that this extended involvement will make scientific progress faster and more adaptable to the needs of the moment, bringing together modelling and measurement, theory and experiment. The effect of feed composition on health and meat quality could be followed through the physiological hierarchy via protein synthesis, metabolic regulation, and growth processes. Shifting feed availability could be met by a coupled optimization of metabolism and economic considerations, based on rapid iteration between feeding experiments, parameter estimation and growth simulations. The fight against new diseases would be guided by a systems understanding of immune responses. For example, candidate vaccines could be tested under the scrutiny of massive phenotyping, revealing what distinguishes an effective response and suggesting new options.

Much of the infrastructure for the Digital Salmon can be lifted directly from the Virtual Physiological Human and the Digital Patient, in particular the standard formats and ontological labelling systems for data and model resources, and "best practices" for the development and use of such resources. However, although there is a long tradition of using existing models and data for other species as a starting point (Niederer *et al.*, 2009), much of the species-specific data and knowledge remains to be developed, and this will require both spadework and innovation.

Phenotyping programmes for salmon will have a strong starting point in existing Norwegian expertise, as built up in the industry, the institute sector and the universities. But the current activity will have to be dramatically expanded and much more concerted. Two important areas of further development are systematic acquisition of -omics data (gene expression, proteomics, metabolomics, etc.), and the linking of these data and massive amounts of other types of phenotypic data to mathematical model parameters and outputs. In a very important sense, parameters are phenotypes too (Vik *et al.*, 2011). Because models differ in their emphasis and level of detail, what is treated as a given parameter in one model could be the output of a more detailed submodel. Moreover, many model parameters show important individual variation (e.g. genetic variation in fatty acid and protein metabolism and its sensitivity to diet, Morais *et al.*, 2012). Thus, parameters in physiological models are phenotypes linked by a causal mathematical structure (Gjuvsland *et al.*, 2013); succinct and relevant summaries of the consequences of underlying mechanisms for higher-level physiology. In most cases we do not yet have technology for measuring such parameters efficiently. Current -omics data cannot be used in a direct way for this purpose, and the linking of such data to models is currently a theme at the research frontier of bioinformatics and high-dimensional data analysis. Focusing on the needs of physiome modelling will drive the construction of new mission-critical measurement technology and new bioinformatics of generic value as well as guide experimental work, greatly increasing the value and generality of the results obtained.

Example applications

Salmon farming in the future must navigate many conflicting demands: maintaining a product that can command top prices in the fish market, making fish grow efficiently on whatever sustainable feedstuffs are available while staying healthy and producing meat with good properties of taste, texture, nutrition and storability; and also dealing effectively with disease challenges. Just as in the Red Queen story, those who stand still will be left behind. This means that there will be no fixed optimal strategy, but rather a strategy for quick adjustment of diet within constraints of price and quality, or rapid development of countermeasures in the face of novel diseases. Such flexibility requires predictive, quantitative models based on integrated knowledge of physiology. In the following we outline four possible applications of the Digital Salmon.

Adapting to alternative feedstuffs

Fish meal is increasingly replaced by plant-based protein sources for reasons of sustainability and economy (Naylor *et al.*, 2009). However, this poses great nutritional challenges, especially for a carnivore such as the salmon (Barrows *et al.*, 2008). Plant feeds have less protein, more starch and fibre, and unfavourable amino acid and mineral profiles (reviewed in Torrissen *et al.*, 2011). Supplementing the feed with vitamins and amino acids which are lacking in plants often fails to have the intended effect. Protein synthesis may increase, but so does the catabolic breakdown of protein (Wacyk *et al.*, 2012). It seems the body responds differently to the crystallized amino acids added to feed than to natural feeds. Furthermore, many plant compounds act as *antinutrients* for salmon, interfering with the absorption of other nutrients (Krogdahl et al., 2010). A prime example is soybean meal, which is well tolerated by many fishes but turned out to cause inflammation of the gut in salmon. Even though the feed industry alleviated this problem by developing soy protein concentrates, we are still facing the fact that current R&D activity on feed development is to a large degree based on a very costly and time-consuming trial and error strategy. A knowledge base allowing reliable prediction of how salmon physiology will respond to a combination of feeds is still a long way off.

In 10 years, a typical salmon feed has changed from containing 10 ingredients including one protein source, to more than 30 ingredients including several protein sources. The feed industry systematically monitors the cost and availability of hundreds of potential feed ingredients and uses this information to minimise production costs while staying within the bounds demanded by physiology. With so many alternative feed ingredients, it is clear that it is grossly inefficient to continue identifying the physiological bounds by specific feed experiments only. We sorely need to establish a systems understanding of metabolism through a Digital Salmon Programme, from which we can predict the physiological consequences of various feed recipes with a minimum of experimental effort.

By domesticating the salmon to mostly a plant diet the salmon industry will escape the accusations of depleting the oceans, but it will not escape the fact that it then has become an ordinary terrestrial meat production industry. As the increasing global meat production is considered by the Food and Agriculture Organization of the United Nations (FAO) to be one of the main drivers behind climate change and loss of biodiversity (FAO, 2006), we should, for several reasons, seriously start to think about developing more environment-friendly solutions for producing salmon feed by advanced industrial biotechnology. One possibility is to start using bacterial protein meal grown on natural gas (Øverland *et al.*, 2010). This solution, which is arguably a sustainable solution when we consider the impact of food production in a wider environmental perspective, is already technologically mature. And a large-scale industrial implementation standing on the shoulders of many years of Norwegian R&D is now under consideration in Malaysia. Furthermore, even though we have known for 25 years that we would run out of naturally available fatty acids, this challenge is only now becoming seriously addressed by the industry and R&D sector. To remedy this extremely serious problem, we either have to produce fatty acids at an industrial scale by novel methods or design a salmon capable of synthesizing these acids. A change to predominantly novel diets produced by means of industrial biotechnology, would strengthen the need for a quantitative systems understanding of salmon metabolism.

The purpose and function of the metabolic system is to adjust the rates of the physiological processes of building up and breaking down, in such a way as to serve the body's needs depending on the state it is in. The model repositories at cellml.org and biomodels.net already contain numerous models of metabolic signal processing and metabolic pathways. The former describe the rapid process of sensing physiological state (e.g. pH, iron concentration, or metabolite concentrations) and propagating the signal (e.g. through conformational switches of enzymes) so as to adjust metabolic activity. The latter describe the longer-term effects of that activity, using the rules of protein physics, mass conservation and chemical stoichiometry. This provides a framework for understanding how metabolic regulation can go awry if the effect of artificial feed components differs from that of their natural counterparts (e.g. Wacyk *et al.*, 2012). An organ model for the gut should be a high priority for the Digital Salmon.

The models and phenomics of a Digital Salmon would pave the way for a predictive, well-tested model of metabolic response and growth performance for a large span of possible diets at the level of the individual fish. Once validated, such a model would become a tool for the industry for rapid optimization of diet composition based on feed prices and requirements for efficient and healthy fish growth. Further refinement of the model or its parameter estimates could be a task for basic and applied research, respectively.

Maintaining product quality

Diet is also important to the quality of the final product. For example, rainbow trout got fatter on soy than on fishmeal when fed amino-acid-balanced diets with either soy or fish-meal as protein source (Wacyk *et al.*, 2012). Even so, the proportion of healthy omega-3 fatty acids in salmon fillets was lower when plant oils replaced fish oils in the feed (Torrissen *et al.*, 2011). Meat redness is another key phenotype, resulting from the uptake, transport and deposition of carotenoid pigments in different tissues; Figure 3 illustrates a model of how these processes depend on sexual maturation (Rajasingh *et al.*, 2006). Because carotenoids are chemically similar to fatty acids, this marks a first step towards systems modelling of fatty acid metabolism in salmon. Understanding the relationship between feed composition and product quality requires additional emphasis on models for describing a wide set of biophysical muscle tissue characteristics of relevance to meat quality. The Digital Salmon will then delineate the regions in "diet space" that ensure satisfactory product quality. This requirement then forms a constraint for economic and industrial optimization as outlined in the previous section.

Managing disease risk

Disease remains a major loss factor in aquaculture, although Norwegian fish farming has successfully dealt with a number of health issues (Norwegian Seafood Federation, 2010). Experience shows that new diseases emerge occasionally, and dealing with these is a big challenge.

It is still early days for integrated mathematical models of the immune system and its responses to pathogens, but the Virtual Physiological Human will blaze the trail for this work too (e.g. Thomas *et al.*, 2013). Consolidating in a Digital Salmon the growing understanding of immune responses is key to being well prepared for dealing with novel diseases. Phenomics for monitoring immune responses to pathogen challenges are already in place, being used to assess whether patients respond effectively to vaccines (Pulendran *et al.*, 2010). Currently, systems vaccinology is mostly limited to clustering analyses of multivariate immune responses, traced through gene regulation, protein expression and blood cell activity on time-scales from hours to days. This high-dimensional phenotype already provides clues to physiological mechanisms by enabling comparison between individuals that respond well to vaccination, non-responders, and healthy individuals. However, to follow up on these clues and realize the full potential of immune phenomics data requires a physiome approach, seeking a systems understanding of how the immune system shapes its response to environmental perturbations by an interplay of system state and immune processes.

Once the Digital Salmon can account for immune responses in terms of mechanism, it forms a framework for rapidly incorporating and interpreting new knowledge such as massive data collection on diseased or vaccinated fish. Furthermore, practical experience with this approach has a good chance of carrying over from one new disease to the next. Pioneering this systems approach with the Digital Salmon would also represent a substantial contribution to general disease biology and Norway's visibility in this research arena.

Preserving wild salmon populations and the marine environment

By keeping the domesticated fish healthier on a more continuous basis, the knowledge base generated by a Digital Salmon Programme would represent a major contribution to the preservation of wild salmon populations. It would also open for a deep systems understanding of the salmon's neurophysiology that could be used to modulate its neurobiological circuitry such that (possibly sterile) escapees do not move into the rivers.

This would put an end to concerns about genetic pollution as well as transmission of diseases in the rivers.

A systems understanding of neuroendocrine regulation and how the fish senses and responds to its environment (West-Eberhard, 2003; Gilbert & Epel, 2009; Bateson & Gluckman, 2011) will also greatly improve insight into the ecology of salmon, and thus its management outside the controlled conditions of fish farms. In general, by making use of Digital Salmon models linking the genome and the phenome in a population dynamics and ecological context, we would be in a much better position to understand how the genetic composition of wild salmon stocks would change as a function of a whole range of changes in their freshwater and seawater habitats not necessarily imposed by the aquaculture industry, and how these changes would affect population numbers (Hedger *et al.*, 2013).

Thus, a Digital Salmon would become a very useful tool in ecosystem-based management of wild salmon populations, and it would tie into large-scale attempts to model the general ecological dynamics in rivers and oceans. A Digital Salmon Programme should have these management aspects built into it.

Making a Norwegian Digital Salmon Programme a reality

The size of a Norwegian Digital Salmon Programme would have to be larger and differently organised than what can be accommodated through a few Centres of Excellence or Centres for Research-based Innovation. But these concepts could very well be exploited under the umbrella of a programme structure that also involves other mechanisms. A Norwegian Digital Salmon Programme would have to be run very differently from how large R&D programmes are currently run by the Research Council of Norway. This does not imply that the current practice is not useful in some contexts, but a Norwegian Digital Salmon Programme should ideally have the following characteristics:

(i) Success criteria that are so explicitly stated that they can be used for programme assessment as well as provide clear guidance for defining programme sub-goals throughout the whole programme period.
(ii) A flexible structure that stays in tune with international developments through very efficient procedures for monitoring programme-relevant changes in technology, methodology and biological knowledge.
(iii) A coherent and closely monitored project portfolio where the outcomes of one project generation would at least in part provide the points of departure for the next generation of projects.
(iv) An integrated and balanced mix of application-focused research and knowledge-oriented research, that not only fulfils overall practical goals but also substantially improves Norway's standing in the international research landscape.
(v) Close links to international academic environments excelling in performing systems biology on model organisms and in systems medicine.
(vi) Openings for funding outstanding international groups to solve problems beyond the reach of Norwegian groups.
(vii) Opportunities for small start-up companies to develop crucial technology and methodology that could later become profitable products on international biomedical markets.
(viii) A close interaction between universities, institute sector, industry, ministries and the Research Council of Norway promoting transparency, division of labour and predictable funding premises allowing the R&D institutions to make long-term commitments.
(ix) A novel programme governance structure reflecting the need for concerted commitments of universities, institute sector, industry, ministries and the Research Council of Norway.

Space restrictions prevent us from elaborating on all the above characteristics, and we therefore focus on points (iv), (vi), (vii), (viii) and (ix).

Integrating different types of research. It is well known that the considerable Norwegian investments in salmon aquaculture research have paid off remarkably poorly in major disciplinary arenas in biology. In the fish biology sector instrumental research (application-focused work disregarding reasons behind phenomena) has been, and is still, the favoured funding object for Norwegian authorities compared to more basic epistemic (knowledge-oriented) research. Instrumental research is likely to continue enjoying the lion's share of future funding unless specific measures are taken to balance the situation. Epistemic research is more highly valued by the international research community and papers published in the high-impact journals in the main disciplinary categories, have in the majority of cases a strong epistemic component. Considering the amount of money spent, Norway is not well represented in these journals. This is an unfortunate situation, because it reflects suboptimal use of research money and negatively affects the quality of instrumental research activity, as it feeds heavily on knowledge generated by curiosity-driven research. The Research Council of Norway is fortunately in a position to remedy this situation by demanding that researchers running application-focused projects should articulate how their data also could be used to provide insights that would receive the attention of important disciplinary journals.

The construction of an ensemble of mathematical descriptions of salmon physiology (including the genomic and environmental dimensions) by merging numerous competences within the life sciences, the mathematical sciences and engineering, would take Norwegian interdisciplinary and interinstitutional collaboration to an unprecedented level. The model construction as such would be a major knowledge-generator in itself. If we find that implementing current conceptions of how a biological system or process works into a quantitative mathematical model that produce results in disagreement with existing or new empirical data, this is a potent source for making new hypotheses about basic biological mechanisms which may result in important contributions to the general biological research frontier. Moreover, the huge amounts of experimental data needed to both construct and test advanced models useful for practical applications would be a treasure trove for discovering new basic patterns of phenomena in need of novel explanations. It would also drive the development of new experimental protocols and new technology for measuring biological processes that would be of instrumental value for international biological research in general. A Norwegian Digital Salmon Programme would thus blend application-focused research and knowledge-oriented research into a concerted whole.

The US National Science Foundation defines *transformative research* as something that "involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers." We anticipate that a Norwegian Digital Salmon Programme would live up to this characteristic in several respects, and even become a role model for government-funded R&D by other countries.

Funding international groups. A Norwegian Digital Salmon Programme would need substantial help from international researchers due to reasons of intellectual and technological bandwidth. Instead of just being based on current practice where Norwegian researchers invite international collaborators on their projects, we suggest that in order to get the attention of the foremost world-wide competence, one should seriously consider establishing a mechanism for financing international mission-critical R&D associated with the Digital Salmon. This could of course be a general mechanism for funding R&D in several fields of particular interest to Norway. But it would be a particularly useful mechanism in connection with a vision-based and tightly governed biotechnology programme like the Digital Salmon, where we want to achieve quite specific, measurable objectives by blending a wide array of competences within the life sciences, the mathematical sciences and engineering.

The potential benefits would be great. We would substantially enhance the positive international attention for Norwegian research while tapping into hundreds of billions NOK of invested capital in competence and infrastructure in other countries. Mission-critical goals would be achieved much faster while not causing an imbalance between number of staff and students at the universities or overstaffing the institute sector. By demanding the participation of Norwegian groups on highly specific terms in these projects, we would drive much larger portions of Norwegian research towards the international elite level with regard to competence, professionalism, and participation in top-tier publications. This would substantially strengthen the Norwegian group's competence, international visibility, and future attractiveness for international collaboration (e.g. with the EU or NIH/United States) and recruitment of PhD students and postdocs. And we could demand a share for Norway in the profits from patentable inventions and other intellectual property emerging from the projects financed.

Establishing new biotech industry. A Norwegian Digital Salmon Programme would demand development of a wide array of phenotyping technologies across the whole phenotypic hierarchy of salmon, ranging from the intracellular level up to the whole individual. It would also demand innovative new software solutions for compiling and analysing high-dimensional data and for linking such data to models. Finally, it would demand the evolution of advanced diagnostics tools, lab-on-a-chip technologies, and new concepts for bioreactor design and synthetic biology engineering for producing salmon feed from new sustainable raw materials. As these technologies would in many cases be directly applicable within biomedical R&D as well as in several other areas of the evolving bioeconomy, this opens an opportunity window for funding start-up companies and established companies to solve mission-critical challenges that later could be introduced on the international market. Such a mechanism would prevent breaking international rules while taking companies through the so-called "valley of death", where initial funding is running out while the product is not yet ready for the market.

Ensuring a concerted national effort. As the Norwegian authorities have not so far defined a clear interface between the institute sector and the university sector in terms of funding mechanisms and clear description of responsibilities (Kunnskapsdepartementet, 2009), it is quite daunting to understand how the authorities plan to realise their dream about a much more pronounced collaboration, division of labour and concentration of efforts and resources (SAK) between and within these two sectors. It is a frequent concern of the industry that much of the institute sector's R&D is not applied enough to really help the industry meet its short-term goals, whereas the universities are lacking the basic competence needed to meet long-term goals characterized by very high innovation thresholds. By having to merge, out of pure necessity, numerous competences within the life sciences, the mathematical sciences and engineering, a Norwegian Digital Salmon Programme would in fact be an ideal instrument for realising, within a very important economic segment, a more pronounced SAK structure. As the industry would also be on board and have a say in this structure, it would facilitate transparent commitments of the industry to agreed-upon R&D goals to a much greater extent than is currently the case. But this would require more leadership by the authorities in connection with programme design and role designation, and their willingness to smoothen the process by financial means.

Concluding remarks

In their book *Et kunnskapsbasert Norge* ("A knowledge-based Norway"), Torger Reve and Amir Sasson make a clear distinction between production of seafood and biotechnology, which they intimately link to the diagnostics and pharmaceutical industries (Reve & Sasson, 2012). This distinction is not in resonance with the fact that the Norwegian salmon production industry is indeed already a biotechnological industry according to the OECD definition. If Reve and Sasson had acknowledged this before discussing the prospects for developing a biotech industry in Norway, it would probably have affected their conclusion.

A Norwegian Digital Salmon Programme would likely have a very positive impact with regard to several of the assessment criteria Reve and Sasson use to classify and qualify the Norwegian knowledge industries: cluster attractivity, educational attractivity, talent attractivity, research and innovation attractivity, ownership attractivity, and environmental attractivity. These aspects should be given close attention when designing the Digital Salmon Programme. A successful design could make this programme a driver for the creation of a biotechnological supply industry that in addition to serving the Norwegian salmon production companies, would find large international markets for their products in a wide array of segments also outside aquaculture. This would echo what has happened in the Norwegian petroleum sector, where the supply industry now delivers advanced technology, products and services for the Norwegian shelf as well as international markets. This success story is very much due to close interaction between the oil companies on the shelf, the supply industry and the R&D environments.

From the 1920s through the 1980s, Bell Labs, the R&D wing of AT&T, was the most innovative scientific organisation in the world. As Jon Gertner argues in his new book, *The Idea Factory*, it was where the future was invented (Gertner, 2012). Bell Labs was behind many of the innovations that have come to define modern life, including the transistor, the laser, the silicon solar cell, the communication satellite, the cellular telephone system and the fibre-optic cable system. Besides access to talent, this success story was based on visionary leadership, forced interdisciplinarity, purpose-guided freedom and institutional patience. Nothing prevents Norway from trying out this recipe to create transformative technology through a Digital Salmon Programme as envisioned above.

In his delightful book *The Black Swan*, Nassim N. Taleb distinguishes between two realms, Mediocristan and Extremistan (Taleb, 2007). Mediocristan is where normality resides and the impacts of events are rather small. In Extremistan, events that seemed unlikely, impossible and even unthinkable occur frequently and have a dramatic impact. Black Swan events occur in Extremistan. Taleb's point is that we should pay much higher attention to the possibility of Black Swan events when we assess the future prospects of things. One can very well make a linear projection of future production volumes of salmon in 2050 from current volumes, but this is a daunting thing to justify, considering the harshness of the Darwinian theatre that the salmon production industry is part of. We would be unbelievably lucky if no Black Swan with dramatic negative impact appeared within the next 40 years if we continue with business as usual (see also Chapter 5 by Tveterås in this book). There are many situations we cannot prepare for, but when it comes to biology, a Digital Salmon Programme would prepare us for a whole range of events that otherwise would develop into Black Swan events.

There is no excuse for not starting preparing for the highly unexpected in terms of building a real pre-emptive knowledge base for salmon biology. Considering that Norway has invested several billion NOK in CO_2-handling R&D, there is apparent willingness to take on risky projects when this is found opportune by those controlling the expenditure of Norwegian oil money. Even without any expansion of volumes, we will from now till 2050 produce 40 million tons with a current market value of >1200 billion NOK. The strong possibility of not being able to realise this value due to lack of knowledge, should be enough reason for spending several billion NOK on a Norwegian Digital Salmon Programme that at the same time would give broad segments of Norwegian science a real boost.

Acknowledgements

We are grateful to Petter Arnesen, Kjetil Hindar, Ole Petter Ottersen, Karl Shearer, Trygve Sigholt, Per Olav Skjervold and Dag Inge Våge for their perceptive comments on the issues discussed here. Figure 3 is based on two Creative Commons licenced images (Kils, 2005; Rajasingh *et al.*, 2006, Figure 1); the composite image is available at http://arken.umb.no/~jonvi/digital_salmon.jpg.

References

Anon (2010). QTL Eggs – Documented IPN protection from day one. *Aqua Gen Information Letter* **2010,** 1.

Barrows FT, Bellis D, Krogdahl Å, Silverstein JT, Herman EM, Sealey WM, Rust MB & Gatlin DM (2008). Report of the Plant Products in Aquafeed Strategic Planning Workshop: An integrated, interdisciplinary research roadmap for increasing utilization of plant feedstuffs in diets for carnivorous fish. *Reviews in Fisheries Science* **16,** 449–455.

Bateson P & Gluckman P (2011). *Plasticity, Robustness, Development and Evolution*. Cambridge University Press.

Beard DA, Neal ML, Tabesh-Saleki N, Thompson CT, Bassingthwaighte JB, Shimoyama M & Carlson BE (2012). Multiscale modeling and data integration in the Virtual Physiological Rat project. *Annals of Biomedical Engineering* **40,** 2365–2378.

De Bono B, Hoehndorf R, Wimalaratne S, Gkoutos G & Grenon P (2011). The RICORDO approach to semantic interoperability for biomedical data and models: strategy, standards and solutions. *BMC Research Notes* **4,** 313.

Carroll L (1871). *Through the Looking-Glass*. Project Gutenberg, http://www.gutenberg.org/ebooks/12.

FAO (2006). *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agriculture Organization of the United Nations.

Gertner J (2012). *The idea factory: Bell Labs and the great age of American innovation*. Penguin Press.

Gilbert SF & Epel D (2009). *Ecological Developmental Biology*. Sinauer Associates.

Gjuvsland AB, Vik JO, Beard DA, Hunter PJ & Omholt SW (2013). Bridging the genotype-phenotype gap: what does it take? *The Journal of Physiology*; DOI: 10.1113/jphysiol.2012.248864.

Gove PB ed. (1981). *Webster's Third New International Dictionary of the English Language, Unabridged*. Merriam, Springfield, MA.

Gurwitz D (2012). High-quality phenomics are crucial for informative omics studies. *Drug Development Research* **73,** 353–356.

Hedger RD, Sundt-Hansen LE, Forseth T, Ugedal O, Diserud OH, Kvambekk ÅS, Finstad AG & Bradford M (2013). Predicting climate change effects on subarctic–Arctic populations of Atlantic salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Sciences* **70,** 159–168.

Houle D, Govindaraju DR & Omholt S (2010). Phenomics: the next challenge. *Nat Rev Genet* **11,** 855–866.

Hunter P *et al.* (2013). A vision and strategy for the virtual physiological human: 2012 update. *Interface Focus*; DOI: 10.1098/rsfs.2013.0004.

Hunter PJ & Borg TK (2003). Integration from proteins to organs: the Physiome Project. *Nat Rev Mol Cell Biol* **4,** 237–243.

Joyce AR & Palsson BØ (2006). The model organism as a system: integrating "omics" data sets. *Nature Reviews Molecular Cell Biology* **7,** 198–210.

Kils U (2005). File:Salmonlarvakils.jpg. *Wikipedia*. Available at: http://en.wikipedia.org/w/index.php?title=File:Salmonlarvakils.jpg&oldid=482663815 [Accessed April 29, 2013].

Krogdahl Å, Penn M, Thorsen J, Refstie S & Bakke AM (2010). Important antinutrients in plant feedstuffs for aquaculture: an update on recent findings regarding responses in salmonids. *Aquaculture Research* **41,** 333–344.

Kunnskapsdepartementet (2009). Klima for forskning. St.meld. nr. 30 (2008-2009). Available at: http://www.regjeringen.no/nb/dep/kd/dok/regpubl/stmeld/2008-2009/stmeld-nr-30-2008-2009-.html?id=556563 [Accessed March 3, 2013].

Land S, Niederer SA, Louch WE, Sejersted OM & Smith NP (2013). Integrating multi-scale data to create a virtual physiological mouse heart. *Interface Focus*; DOI: 10.1098/rsfs.2012.0076.

Lanktree MB, Hassell RG, Lahiry P & Hegele RA (2010). Phenomics: expanding the role of clinical evaluation in genomic studies. *Journal of Investigative Medicine* **58,** 700–706.

Lieschke GJ & Currie PD (2007). Animal models of human disease: zebrafish swim into view. *Nat Rev Genet* **8,** 353–367.

Merriam-Webster (2008). *Webster's Third New International Dictionary, Unabridged*. Available at: http://unabridged.merriam-webster.com.

Morais S, Silva T, Cordeiro O, Rodrigues P, Guy DR, Bron JE, Taggart JB, Bell JG & Tocher DR (2012). Effects of genotype and dietary fish oil replacement with vegetable oil on the intestinal transcriptome and proteome of Atlantic salmon (Salmo salar). *BMC Genomics* **13,** 448.

Naylor RL, Hardy RW, Bureau DP, Chiu A, Elliott M, Farrell AP, Forster I, Gatlin DM, Goldburg RJ, Hua K & Nichols PD (2009). Feeding aquaculture in an era of finite resources. *PNAS* **106,** 15103–15110.

Niederer SA, Fink M, Noble D & Smith NP (2009). A meta-analysis of cardiac electrophysiology computational models. *Experimental Physiology* **94,** 486–495.

Norwegian Seafood Federation (2010). Health situation of farmed salmonids since 1990. *Norwegian Seafood Federation Factsheets*. Available at: http://www.fhl.no/getfile.php/DOKUMENTER/Faktaark_laksesykdommer%201990%20-2009ENG.pdf [Accessed March 6, 2013].

Noy NF, Shah NH, Whetzel PL, Dai B, Dorf M, Griffith N, Jonquet C, Rubin DL, Storey M-A, Chute CG & Musen MA (2009). BioPortal: ontologies and integrated data resources at the click of a mouse. *Nucl Acids Res* **37,** W170–W173.

OECD (2005). Statistical Definition of Biotechnology. Available at: http://www.oecd.org/sti/biotech/statisticaldefinitionofbiotechnology.htm [Accessed April 26, 2013].

Olafsen T, Winther U, Olsen Y & Skjermo J (2012). Value created from productive oceans in 2050. *Report of the Royal Norwegian Society of Sciences and Letters and of the Norwegian Academy of Technological Sciences*. Available at: http://www.sintef.no/home/Fisheries-and-Aquaculture/News/Value-created-from-productive-oceans-in-2050/ [Accessed March 3, 2013].

Olsen OA (1989). *Structured modelling of fish physiology.* Dr. Ing. dissertation 1989:37, Norwegian Technical University, Department of technical cybernetics, Trondheim.

Omholt SW (2012). From sequence to consequence and back. *Progress in Biophysics and Molecular Biology*; DOI: 10.1016/j.pbiomolbio.2012.09.003.

Pulendran B, Li S & Nakaya HI (2010). Systems Vaccinology. *Immunity* **33,** 516–529.

Rajasingh H, Gjuvsland AB, Våge DI & Omholt SW (2008). When parameters in dynamic models become phenotypes: a case study on flesh pigmentation in the chinook salmon (Oncorhynchus tshawytscha). *Genetics* **179,** 1113–1118.

Rajasingh H, Øyehaug L, Våge DI & Omholt SW (2006). Carotenoid dynamics in Atlantic salmon. *BMC Biology* **4,** 10.

Reve T & Sasson A (2012). *Et kunnskapsbasert Norge*. Universitetsforlaget, Oslo, Norway. Available at: http://www.bokkilden.no/SamboWeb/produkt.do?produktId=5774939 [Accessed April 3, 2013].

Taleb NN (2007). *The Black Swan: The Impact of the Highly Improbable*. Penguin Press.

Thomas N, Heather J, Pollara G, Simpson N, Matjeka T, Shawe-Taylor J, Noursadeghi M & Chain B (2013). The immune system as a biomonitor: explorations in innate and adaptive immunity. *Interface Focus*; DOI: 10.1098/rsfs.2012.0099.

Torrissen O, Olsen RE, Toresen R, Hemre GI, Tacon AGJ, Asche F, Hardy RW & Lall S (2011). Atlantic salmon (Salmo salar): The "super-chicken" of the sea? *Reviews in Fisheries Science* **19,** 257–278.

Vik JO, Gjuvsland AB, Li L, Tøndel K, Niederer SA, Smith NP, Hunter PJ & Omholt SW (2011). Genotype–phenotype map characteristics of an in silico heart cell. *Frontiers in Physiology* **2,** 106.

Wacyk J, Powell M, Rodnick K, Overturf K, Hill RA & Hardy R (2012). Dietary protein source significantly alters growth performance, plasma variables and hepatic gene expression in rainbow trout (Oncorhynchus mykiss) fed amino acid balanced diets. *Aquaculture* **356–357,** 223–234.

Weinstein JA, Jiang N, White RA, Fisher DS & Quake SR (2009). High-throughput sequencing of the zebrafish antibody repertoire. *Science* **324,** 807–810.

West-Eberhard MJ (2003). *Developmental Plasticity and Evolution*. Oxford University Press, USA.

Wiktionary (2013). Wiktionary. Available at: http://en.wiktionary.org [Accessed June 20, 2013].

Øverland M, Tauson A-H, Shearer K & Skrede A (2010). Evaluation of methane-utilising bacteria products as feed ingredients for monogastric animals. *Archives of Animal Nutrition* **64,** 171–189.

Growth and Innovation in Aquaculture: Can the Blue Revolution Continue?

Ragnar Tveterås
Professor, University of Stavanger Business School,
ragnar.tveteras@uis.no

Introduction

Aquaculture faces global demographic and socio-economic trends that should ensure continued growth in consumer demand in the future. A rising global awareness of the benefits of seafood, together with population growth, will lead to increased seafood demand in the future. A growing and large body of scientific research has documented the benefits of seafood in the human diet (Nesheim and Yaktine, 2007; FAO/WHO 2011). Consumers will not only demand more seafood but also increased product quality and diversity as they become wealthier (Jensen, 2006). Finally, the global population will continue to increase, although at lower rates than we have seen earlier.

Despite local and global constraints due to environmental challenges and competing user interests, aquaculture has to provide most of the future growth in seafood production, since most of the world's fish stocks are fully exploited or over-exploited (Smith et al., 2010a). During the last decades aquaculture has been the world's fastest growing food production technology, creating a blue revolution (Asche, 2008). Furthermore, aquaculture is better positioned than fisheries to provide the product quality and diversity that future consumers will demand, as the higher degree of control with the production process facilitates innovation in both production processes and products (Anderson, 2002; Asche, 2008; Asche, Roll and Tveterås, 2009).

The rapid innovation-driven expansion of intensive, commercial aquaculture in the decades after the Green Revolution in the 1970s has been described as a 'Blue revolution', and has been highlighted in influential publications such as the Economist (2003a,b). Aquaculture has been expected by the Food and Agriculture Organization of the United Nations (FAO) and others to be a major source of protein growth to a growing and more affluent global population (FAO, 2008, 2012). However, there are concerns about constraints facing aquaculture and their effects on future growth (FAO, 2008, part 4).

Policy makers and other stakeholders have high ambitions for the growth of global protein supply from aquaculture. To achieve these ambitions different policies have been implemented by national and regional governments to facilitate growth.
In this chapter we examine the following issues:

1 How is global aquaculture production developing?
2 Which factors influence growth in aquaculture at different stages?
3 What patterns of growth do we see at the more disaggregated level, in individual country/species sectors?

Finally, we draw some implications on the future prospects for global aquaculture.

Global aquaculture production growth

As stated above, growth ambitions for aquaculture have been and continue to be high. But how have global aquaculture production growth rates really developed over time?

Figure 1 shows the development of production volume and 5-year moving average production growth in percent from 1955 to 2010, the last year FAO has data on. Aquaculture includes production of fish, crustaceans, molluscs, seaweeds and plants. We see that production has increased from around one million tonnes in 1955, to 3.5 million tonnes in 1970, and 79 million tonnes in 2010. The growth rate has fluctuated over time. However, we see that after 2000 the growth rate has been lower than in the previous decades, at a level of 6-7%. In fact, during the 1980s production increased by 170%, then declined to 130% in the 1990s, and in the decade starting in 2000 production has only increased by 76%.

FAO's data ends in 2010. More recent data on some of the main aquaculture sectors suggest that the decline in growth rates compared with earlier periods has continued after 2010 (Tveterås, 2012).

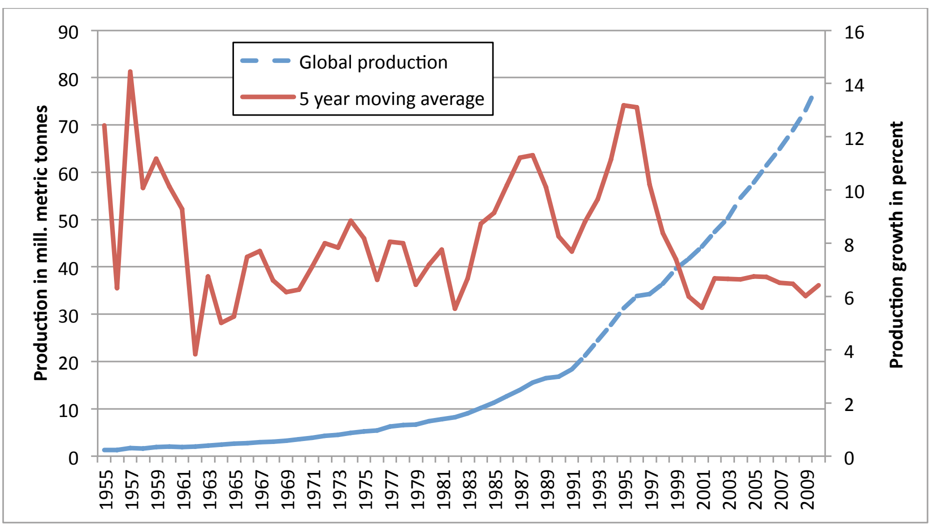


Figure 1. Global aquaculture production volume in metric tonnes and 5-year moving average production growth in percent. (Data source: FAO Fishstat)

The development of aquaculture production has been very unequal across the world's regions, as shown in Table 1. We see that Asia has increased its share of global production from 70% in 1970 to 89% in 2010. China is the global aquaculture giant with a production that increased from 30% of the world total in 1970 to 61% in 2010. Europe is the big loser in terms of global market share, as its production share declined from 22.4% in 1970 to 4.2 percent in 2010. In general, this implies that production has increased more rapidly in developing countries than in developed countries.

Region	1970	1980	1990	2000	2009	2010
Asia	70.1	75.5	82.6	87.7	88.9	89.0
- China	29.8	28.0	49.6	66.4	62.4	61.4
Americas	6.8	4.2	4.2	4.4	4.5	4.3
Europe	22.4	19.5	12.2	6.3	4.5	4.2
Africa	0.4	0.6	0.6	1.2	1.8	2.2
Oceania	0.3	0.3	0.3	0.4	0.3	0.3

Source: FAO (2012)

Table 1. Percent share of global aquaculture production.

Determinants of aquaculture growth

To understand the development of aquaculture production at the aggregate global level and the opportunities and barriers for the future, one needs to understand the factors which influence growth at the individual sector level. This section will discuss factors that influence growth.

Drivers of growth are found both on the supply and demand side. Productivity growth driven by innovations is a central determinant of production growth in the long run, as it typically leads to lower production costs. In the next stage this allows producers to expand production in a profitable manner even at lower prices. Shifts in market demand can also allow for growth through positive shifts in the market price at higher production levels. An example of a sector where both productivity growth driven by innovations and shifts in market demand have caused production growth is Norwegian salmon aquaculture (Asche, Roll and Tveterås, 2009, 2012).

In aquaculture the following underlying factors which influence productivity and growth should be pointed out: (a) *Innovation* in key areas; (b) *externalities* within aquaculture, particularly related to disease and fish health, and externalities to other sectors and users; and (c) exploitation of *internal and external returns to scale*.

In the following we will discuss each of these factors.

a Innovation in key areas.

During the 1970s and 1980s humanity's accumulated knowledge and innovations in aquaculture allowed the introduction of more semi-intensive and intensive farming practices, and the production cycle was closed for an increasing number of species. The control of the production process that was achieved enabled a number of productivity-enhancing innovations to take place.

Examples of innovations that have generally increased productivity and sustainability in aquaculture and thus contributed to growth are:

- Feed and feeding equipment innovations which have contributed to more efficient conversion of feed to fish, lower local organic emissions, lower inclusion of fish oil and fish-meal, etc.
- Vaccine innovations, which have reduced mortality, reduced use of antibiotics, etc.
- Genetic innovations (breeding), which have contributed to more efficient conversion of feed to fish, increased growth rate, increased disease resistance, etc.
- Farm infrastructure innovations, such as fish cages, monitoring equipment and information technologies embodied in them, which have increased robustness to exposed sea areas, reduced risk of fish mortality and escape, reduced labour intensity, etc.

Several aquaculture sectors, including salmon aquaculture, have evolved from a technological regime with a poor degree of control of many processes to one that can be described as approaching 'biological manufacturing' (Asche et al., 1999; Tveterås, 2002; Tveterås and Battese, 2006). Technologically leading aquaculture sectors have moved from a labour-intensive production where workers had few formal skills, to a production which is more capital-intensive and where computer hardwareand software-based technologies have replaced several of the manual tasks. At salmon farms, for example, the monitoring of the fish, feeding, and environmental variables are based on sophisticated information technologies. Labour input in the sector has become more specialised, with a much higher proportion of labour with a variety of university educations.

For carnivorous species the supply of marine feed ingredients is limited by wild fish stocks. Unless there are radical innovations in e.g. production of algae or plant-based fish oil substitutes, several sectors will have to further reduce inclusion rates for fish oil (and also for fish meal) in order to grow (Tacon and Metian, 2008).

In the 'innovation system' related to aquaculture technology the government can play a central role through legislation, policies and funding. A technological innovation system can be defined as 'a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology'. The private participants in the innovation system include the farming companies and their suppliers, feed companies, equipment and software suppliers, pharmaceutical companies, etc. Universities and related research institutions can also play an important role, both as suppliers of trained labour and researchers, and through the R&D they have undertaken (Asche, Roll and Tveterås, 2012).

R&D is critical for many future radical innovations that are required to ensure growth. However, in aquaculture R&D there is a high economic risk and low degree of appropriability of R&D benefits, i.e. inability to get sufficient private economic returns for private firms investing in R&D. This represents a huge challenge in several areas and for some phases of technological development. A combination of private and public funding is therefore necessary, possibly supplemented by a government mandated levy on the sales revenue of all firms in the sector for R&D funding. Without government intervention in the form of R&D subsidies, R&D levies or other measures, the innovations that aquaculture needs to achieve its potential for sustainable growth may not be realised.

b Externalities within aquaculture, particularly related to disease and fish health, and externalities to other sectors and users.

Externalities are effects of a firm's production activities on other firms, households or other agents which are not fully internalised in the economic decision of the firm because it does not have to cover the economic losses to others associated with the externality. These costs can be in the form of lost sales or increased unit cost for other firms, increased health costs for households, etc. Fish disease is an example of an externality in aquaculture. If a disease outbreak is caused by the production processes at a farm it can be regarded as an externality if other farms are affected by the disease outbreak and the farm does not have to cover all economic losses of other farms (Asche, Guttormsen and Tveterås, 1999; Asche, Roll and Tveterås, 2009). Figure 2 shows different types of externalities from a farm to other farms in the sector, and to other sectors and users.

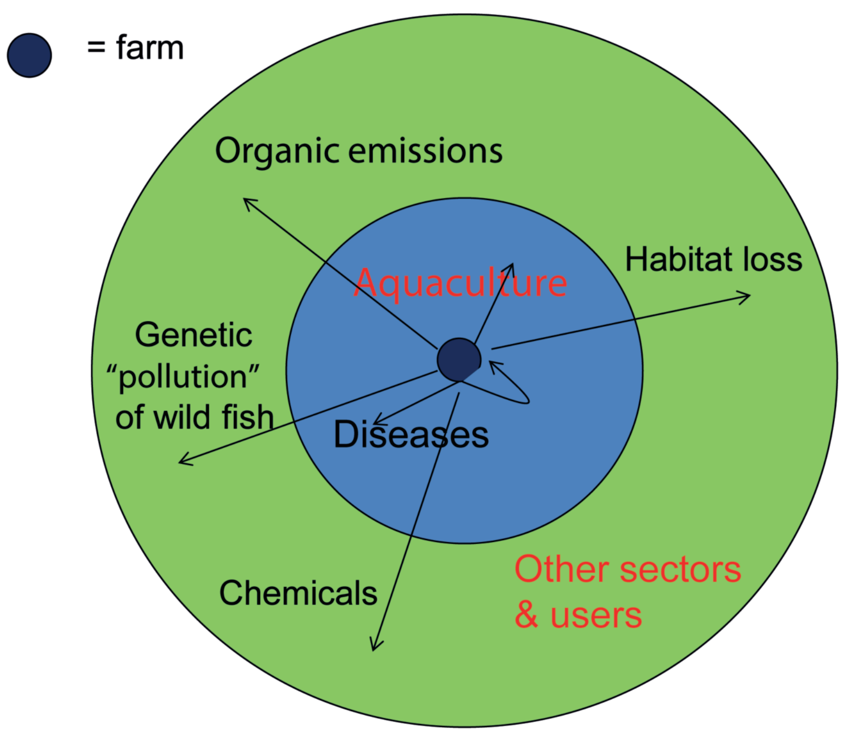


Figure 2. Externalities from aquaculture.

Many aquaculture sectors arguably have larger inherent negative animal disease externalities than agricultural livestock production, such as poultry and pig production, because production is less closed. Open cage production technologies are particularly exposed to disease externalities, depending on water flows, water traffic and density of farms, etc. Fish disease outbreaks have been of such a scale that they have in some cases almost wiped out production in entire sectors, for example, in Asian shrimp aquaculture. Furthermore, some sectors have never recovered after disease outbreaks.

Externalities to other sectors and users can come in several forms, as suggested by Figure 2. Examples are organic emissions that pollute waters and change the nutrient balance, habitat loss (e.g. of mangrove habitat), emission of toxic chemical used to combat disease, escape of farmed fish that "pollute" the genetic pool of wild fish stocks, etc.

In aquaculture externalities influence productivity and production (1) directly through diseases and other externalities that cause increased mortality or lower growth rates, and (2) indirectly through public regulations and other policy measures motivated by externalities. In theory, externalities provide a rationale for government to introduce regulations or taxes to mitigate these. However, in practice the design of appropriate measures will often be a difficult task for governments due to insufficient information about mechanisms and magnitudes of externalities. Measures to mitigate externalities can often fail because their effects are too small or too large, or because they have unintended effects.

Atlantic salmon farming is an example of a farmed species where basically the same production technology is used across countries, but where government measures designed to mitigate externalities differ significantly. The policy measures that have been implemented in the main salmon producer countries have of course also been motivated by other policy objectives, which again have been influenced by the political power of different stakeholders. It can be argued that policy measures that aimed to mitigate externalities, or the absence of these, have had significant effects on the development of production in salmon producer countries. Figure 3 shows the development of Atlantic salmon production in the main

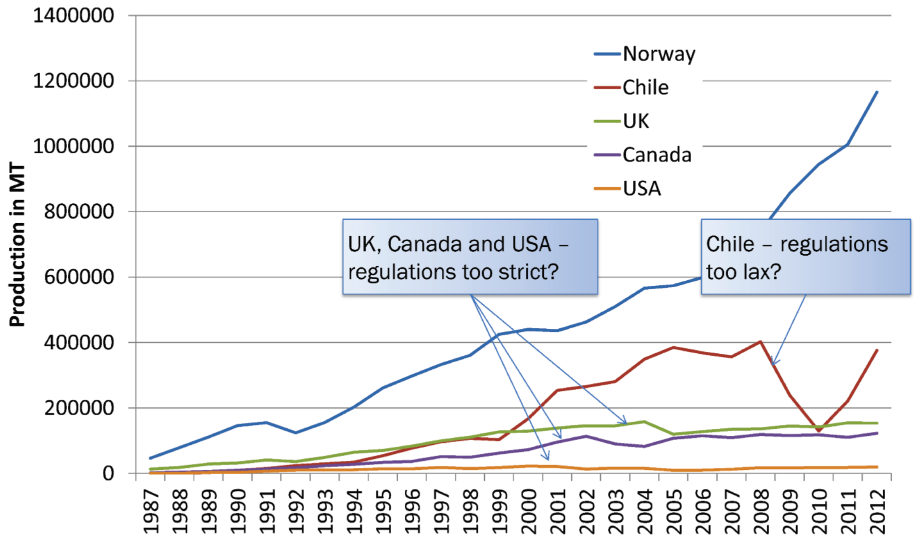


Figure 3. Atlantic salmon production in main producer countries. (Data source: FAO and Kontali)

producer countries. It can be argued that for UK, Canada and USA fairly strict regulations have led to lower environmentally sustainable growth than could have been possible. In the more liberally regulated Chilean sector, the absence of proper regulations has led to a decline in production from 2008 that could have been avoided (Asche et al., 2009).

One important aspect of innovations in the aquaculture sectors, including the examples mentioned earlier in this section, is that they often contribute to reducing the externalities in aquaculture. For example, new feed innovations often lead to smaller organic emissions, healthier and less disease-prone fish. New vaccines may reduce the need for using antibiotics or chemicals. In the future, the combination of innovations and government regulations will determine the magnitude of externalities from aquaculture and the potential for sustainable growth.

c Exploitation of internal and external returns to scale.

There are probably both internal and external returns to scale in aquaculture production in many sectors. *Internal returns to scale* are present when a 1% increase in input levels (labour, capital, feed, etc.) leads to more than a 1% increase in production. Hence, when there are increasing returns to scale at a farm or in a firm, production costs per unit decline because of more efficient use of capital equipment, labour, etc. Several studies have found increasing internal returns to farm and firm size, e.g. Tveterås (2002) and Asche, Roll and Tveterås (2009) for salmon farming. Moreover, the studies suggest that innovations have increased the optimal scale of production, i.e. the scale that provides the lowest production cost per unit, implying that in order to be competitive farms and firms have had to increase their size over time.

External returns to scale are analogous to internal returns to scale, and are present when an increase in the scale of production in a sector, or related sectors, leads to increased productivity and reduced cost per unit. There are several sources of external returns to scale. One potential source is "denser" markets for specialised inputs. For several types of capital equipment used by the aquaculture industry, full capacity utilisation requires that several or many farms demand their services. Moreover, the industry demands specialised expertise in management, export marketing, installation and maintenance of capital equipment, production monitoring, veterinary services, biology, etc. Provision of specialised producer services to the industry requires a certain minimum market size. It can be asserted that an increase in the size of a country's aquaculture industry at some stages can lead to the provision of more productive specialised physical and human capital inputs which will increase productivity.

Increased knowledge spillovers are another source of external returns. As the size of an industry or related industry increases, the scope for different arenas where firms and knowledge providers meet to exchange ideas and knowledge increases. Moreover, the opportunities for migration of human capital between firms, and between firms and surrounding institutions, increase with industry size. A larger industry also allows for capacity increase in education and research institutions oriented towards the industry.

External returns to scale which are geographically constrained to a country or a region are also called *agglomeration economies*, and they give rise to geographically concentrated clusters of firms and related institutions. According to the econometric estimates of Tveterås (2002) and Tveterås and Battese (2006) on salmon farming, there are significant productivity gains and cost savings associated with location in regions with a large salmon aquaculture industry, suggesting the presence of positive external returns to scale, i.e. positive agglomeration externalities. Although the results of these studies are based on salmon farming data, other aquaculture sectors have similar characteristics that should give rise to increasing external returns to scale.

Aquaculture sectors' growth patterns

We will now move down to a more disaggregated aquaculture sector level and examine growth patterns. In the following we define aquaculture sectors by species and country. For example, a sector could be turbot aquaculture in Spain, or Atlantic salmon farming in Norway.

The story about global aquaculture sectors is not the story about the tree that grew into space. Few aquaculture sectors exhibit a steady increase in production over a longer time period. On the contrary, the story about aquaculture sectors is often one of stagnation, decline and even death. It is a story about economic risk in many dimensions (Tveterås, 1999).

The growth in total aquaculture production shown in Figure 1 is the result of the growth and decline of individual sectors, and the entry and exit of sectors. Each year a new cohort of aquaculture species/country sectors have entered the industry. Together with the existing aquaculture sectors the new cohorts have contributed to the growth in total production.

Figure 4 provides an illustration of the huge variations or riskiness of aquaculture. Each red dot is an aquaculture sector in a country. The point shows the sector's production in 2010 on the horizontal axis and the sector's production in the year it had its highest production since its establishment - the historical maximum production so far. If all sectors experienced a steady growth without decline the red points would be close to the blue line. But we see that this is not the case. Only a few of the industries were close to their historical maximum in 2010. Many industries had a production in 2010 that was significantly lower than the historical maximum.

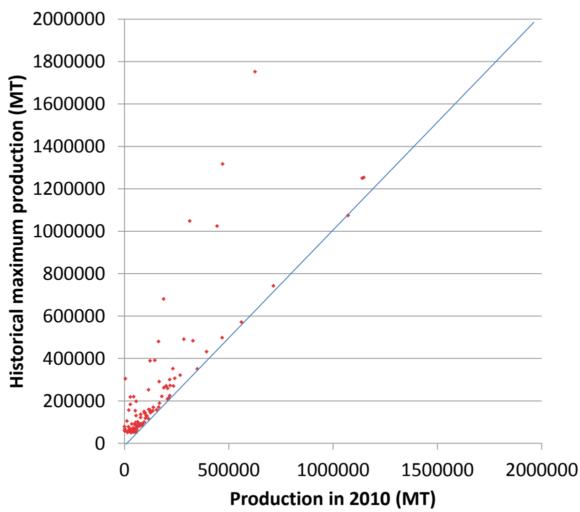


Figure 4. Individual aquaculture sectors' production in 2010 versus their historical maximum production since their establishment. (Data source: FAO)

Table 2 provides a summary of production in the observed sectors in the database for only the last data year, 2010[1]. We see that there are a total of 1 909 sector observations in 2010. The average sector produced 41 thousand metric tonnes, the smallest sector (close to) zero and the largest sector 4.4 million metric tonnes.

One interesting observation is the large difference in average size of aquaculture sectors between regions. The average Asian sector produced 97 thousand MT in 2010, while in Europe average sector production was only 4 thousand MT. If we distinguish between developed and developing countries, we see that the average sector in developing countries is almost ten times larger than the average sector in developed countries. Aquaculture sectors are particularly large in China, as we see at the bottom of the table, with the average sector producing 537 thousand MT in 2010. To some extent these differences in average sector size can reflect underreporting of smaller sectors by developing countries because of fewer resources in statistical agencies, etc. The difference is nevertheless so large that if there are economies of scale at the sector level this may significantly

1 Appendix A shows the same summary statistics for all sector observations from 1950 to 2010.

influence the competitiveness of comparable aquaculture sectors in Europe and other developed countries.

	No. of sectors	Average sector prod. (MT)	Sector st.dev. of prod. (MT)	Smallest sector (min. prod.) (MT)	Largest sector (max prod.) (MT)	Total production (mill. MT)
World	1 909	41 353	276 183	0	4 418 010	78.9
World regions:						
Africa	234	6 104	37 793	0	527 049	1.4
Asia	747	96 658	433 529	0	4 418 010	72.2
Europe	609	4 143	39 540	0	927 876	2.5
Latin America	228	8 478	30 592	0	223 313	1.9
North America	40	16 411	39 289	0	217 204	0.7
Oceania	51	3 901	13 961	1	95 168	0.2
Developed vs developing countries:						
Developed	694	6 499	42 285	0	927 876	4.5
Developing	1 215	61 261	343 176	0	4 418 010	74.4
China	89	537 411	1 008 673	16	4 418 010	47.8
Norway	11	91 637	277 850	2	927 876	1.0

Table 2. Production of all aquaculture sectors in the last data year, 2010.

Table 3 shows the average values of characteristics of species/country sectors for 2010 only. The first column shows the average production in a sector, which is the same as shown in Table 2 above. In the second column is the average production in all aquaculture sectors at the country level. For the entire World, the average country level production in 2010 was 2.7 million MT. We see that Asian countries had much higher production on average than other regions, with an average of 6.7 million MT. European countries, on the other hand, only had an average production of 99 thousand MT. In general, developing countries have much larger aquaculture sectors at the country level with an average production of 4.2 million MT, versus only 152 thousand MT in developing countries. And China is the giant, with a production of 48 million MT in 2010.

Another interesting figure is the ratio of historical maximum production in a sector relative to production in 2010. This was illustrated for a subset of sectors in Figure 4 above. The ratio gives one indication of the riskiness of aquaculture production, and bottlenecks that the sector has faced during its lifetime. The world average ratio of historical maximum production in a sector relative to production in 2010 is 0.62, implying that the average sector in 2010 produced 62% of what it had in the year with highest production during its lifetime. Asian sectors had a ratio of 66%, while European sectors had the lowest with only 52%. Africa sectors' production in 2010 was actually the highest with a ratio of 73%.

	Production in sector (MT)	Production in all sectors in country (MT)	Production 2010 / Historical max. production	Age of sector in years
World	41 353	2 708 984	0.62	20.1
World regions:				
Africa	6 104	101 958	0.73	17.9
Asia	96 658	6 740 469	0.66	23.5
Europe	4 143	98 896	0.52	17.2
Latin America	8 478	155 495	0.62	17.1
North America	16 411	378 398	0.62	30.5
Oceania	3 901	32 247	0.73	19.4
Developed vs developing countries:				
Developed	6 499	152 360	0.54	19.3
Developing	61 261	4 169 311	0.67	20.5
China	537 411	47 800 000	0.88	18.6
Norway	91 637	1 008 010	0.70	19.1

Table 3. Average values of characteristics of species/country sectors in 2010.

To further underscore the risks and potential bottlenecks facing aquaculture sectors, Figure 5 provides some examples of fairly large aquaculture sectors that have experienced rise and fall, or "boom and bust". There are different stories behind these curves, some of them hide large-scale disease outbreaks, but together they illustrate the risks of global aquaculture. A common feature is that quite a few industries have a relatively high and steady growth from a low initial level, but when they reach a certain size, production becomes much more volatile and declines to lower levels than the maximum. Several of the sectors included in Figure 5 have had a maximum production that was two or three times higher than the production in the last data year, 2010.

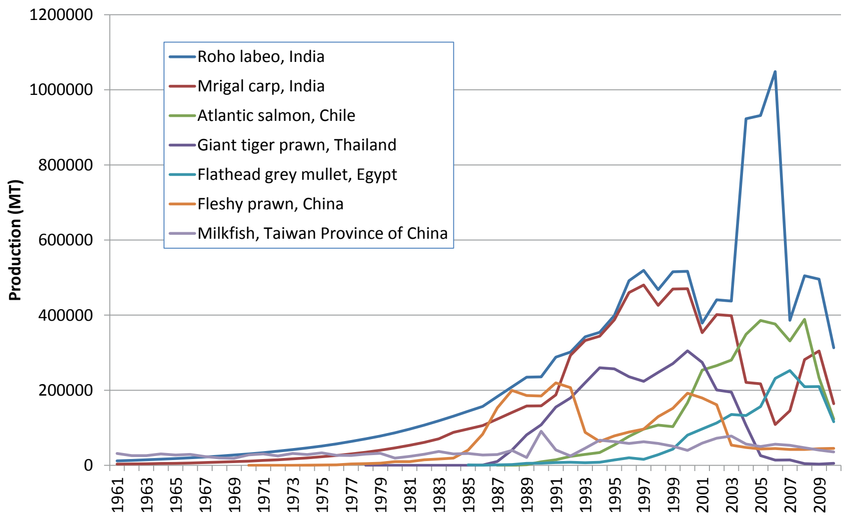


Figure 5. Production in selected aquaculture sectors.

Econometric analysis of growth

This section analyses the causes of production growth rates using econometric panel data models on FAOs Fishstat data set of around 2000 species-country level aquaculture sectors. Based on the econometric estimates we discuss the potential for future growth in global aquaculture. We test hypotheses on the effects on aquaculture sector growth rates of the following:

- Internal scale of sector.
- Scale of other aquaculture sectors in the same country.
- Age of sector.
- Observation year.

Both for the internal scale of the sector and the scale of other aquaculture sectors in the same country we implicitly test for increasing or decreasing returns to scale. If there are increasing returns to scale this should contribute to higher growth rates, while if returns to scale are decreasing this should contribute to lower growth rates. As pointed out earlier, sources of increasing external returns may be increased knowledge spillovers, and increased competition and emergence of specialised, highly productive, input suppliers. On the other hand, negative (congestion) externalities in the form of diseases, organic emissions, habitat destruction, etc. may be sources of decreasing external returns to scale.

Broader returns to scale related to the size of other aquaculture sectors may be related to increasing public aquaculture-specific infrastructure that is made possible by the total size of aquaculture in the country. This aquaculture-specific infrastructure may be in the form of public education institutions, R&D institutions, extension services, specialised private input suppliers, etc.

Sector age is measured from the first year production is observed, and can be a proxy for learning and innovation in the sector. One question is whether there is more innovation and learning in the early years of an aquaculture, and thus a greater effect on growth.

Time measured by year is included to account for unobserved factors that may influence growth rate development over time. One unobserved factor may be the development of the innovation rate, or rate of exogenous technical progress, in aquaculture over time. Another factor may be change in the scarcity of inputs over time, e.g. land area, sea area, marine feed input sources, etc. Finally, time may also account for shifts in consumer demand for seafood from aquaculture.

Different specifications of the following econometric growth model are estimated:

$$\ln Y_{it} - \ln Y_{it-1} = \alpha_i D_i + \beta_{dy1}(\ln Y_{it-1} - \ln Y_{it-2}) + \beta_{dy2}(\ln Y_{it-2} - \ln Y_{it-3}) + \beta_{y1}\ln Y_{it-1} + \beta_{y12}(\ln Y_{it-1})^2 + \beta_{e1}\ln E_{it-1} + \beta_{e12}(\ln E_{it-1})^2 + \beta_a age + \beta_{aa} age^2 + \beta_t t + \beta_{tt} t^2,$$

where i = aquaculture sector subscript (defined by species and production country), t = year, Y = production volume in metric tonnes, E = production volume in other aquaculture sectors in same country in metric tonnes, *age* is age of sector in years.

In some specifications the time trend variable is replaced by year dummy variables to allow for more flexible time-specific effects. Various specifications of sector-specific effects are also tested, including random and fixed sector-specific effects. The model is estimated with robust standard errors. We also test weighted models using production volume as weight, in order to allow larger sectors to influence estimates more than smaller sectors.

Due to space constraints the full set of econometric results from different specifications is not presented here. Results from only one specification are shown here as an illustration, and then a summary of the findings from different model specifications is presented.

Table 4 provides the estimated elasticities from the above econometric model specification. The elasticities are obtained by partial derivation of the estimated model with respect to the explanatory variables. We see for this particular specification that the effect of sector size on growth rate is significantly negative, while the size of the other aquaculture sectors has a significantly positive effect on the growth rate. Furthermore, the age of the sector has a significantly negative effect on growth. Finally, after having controlled for these factors, the model predicts that the growth rate increases over time. For the age and time variable, however, these results are not necessarily representative across estimated models, as suggested below in the summary of empirical results.

Variable	Coef.	Std. err.	t-value	P-value
Sector size	-0.32021	0.02773	-11.55	0.000
Size of other aquaculture sectors	0.04225	0.00516	8.19	0.000
Age of sector	-0.00225	0.00115	-1.97	0.049
Time	0.00238	0.00072	3.32	0.001

Table 4. Estimated growth rate elasticities from weighted least squares model with robust standard errors.

Number of observations: N=34480. Explanatory power: R-squared=0.2235.

The results from a range of different econometric model specifications can be summarised as follows:

- The scale of the sector generally has a significantly negative effect on the growth rate.
- The scale of other aquaculture sectors in the same country tends to have a significantly positive effect on growth rates.
- The age of the sector has ambiguous effects on growth rates, but tends to be positive when the effect is statistically significant.
- The growth rate in most models tends to decline over time after having controlled for the other factors above.

Concluding remarks

We have found that contrary to high expectations from policy makers and others the growth rate of global aquaculture seems to be declining. Moreover, the growth rate is slower in developed countries than in developing countries.

The declining growth rate is not unexpected given the many challenges the sector faces. Aquaculture is a sector with significant externalities both within the sector and to other sectors and users. Fish disease is an important externality within the sector, while externalities to other sectors include emissions of organic material and chemicals, habitat destruction, and genetic modification of wild fish stocks through escape of farmed fish. The aquaculture sector, including government, has to innovate to mitigate externalities as it grows.

Increasing production in coastal regions tends to cause increased negative external effects in the form of fish diseases and different forms of pollution unless the aquaculture industry innovates and improves practices mitigating these externalities (Anh et al., 2010).

Genetic innovation, primarily through fish breeding programmes, has to be a source of productivity growth in more aquaculture sectors than we see today. Traditional selective fish breeding as well as genetic engineering provide opportunities also for future growth as many species have been subject to little research and innovation. However, there are significant barriers facing genetic innovation in the form of classical R&D market failures, regulatory constraints and risks associated with consumer acceptance (Aerni, 2004; Smith et al., 2010b).

In sum, aquaculture production has to continue the transition from a technological regime with limited degree of control of many processes to one that can be described as approaching 'biological manufacturing'. This shift has to be driven by innovations in key technologies. Innovations will allow for productivity growth, and be translated into declining production costs, historically a central cause of the global growth of aquaculture production.

Literature

Anh, P.T., Kroeze, C., Bush, S.R. and Mol, A.P.J. (2010). Water pollution by Pangasius production in the Mekong Delta, Vietnam: causes and options for control, *Aquaculture Research* 42, 108-128.

Aerni, P. (2004). Risk, regulation and innovation: The case of aquaculture and transgenic fish. *Aquatic Sciences* 66, 327-341.

Arquitt, S., Honggang, X. and Johnstone, R. (2005). A system dynamics analysis of boom and bust in the shrimp aquaculture industry. *System Dynamics Review* 21, 305-324.

Anderson, J.L. (2002). Aquaculture and the Future. *Marine Resource Economics* 17, 133-52.

Anderson, J.L. (2003). The International Seafood Trade. Cambridge: Woodhead Publishing. 222 pp.

Asche, F. (2008). Farming the sea. *Marine Resource Economics* 23, 527-547.

Asche, F., Guttormsen, A.G. and Tveterås, R. (1999). Environmental problems, productivity and innovations in Norwegian salmon aquaculture. *Aquaculture Economics and Management* 3, 1-29.

Asche, F., Hansen, H., Tveterås, R. and Tveterås, S. (2009). The salmon disease crisis in Chile, *Marine Resource Economics* 24(4), 405-412.

Asche, F., Roll, K.H. and Trollvik, T. (2009). New aquaculture species – the whitefish market. *Aquaculture Economics and Management* 13, 76-93.

Asche, F., Roll, K.H. and Tveterås, R. (2009). Economic inefficiency and environmental impact: an application to aquaculture production. *Journal of Environmental Economics and Management* 58, 93-105.

Asche, F., Roll, K.H. and Tveterås, R.. (2012). Salmon Aquaculture's Innovation Process towards Biological Manufacturing: Past Performance and Future Challenges. Proceedings, International Conference on Advances in Production Management Systems (APMS). Stavanger, 26-28 September 2011. Published in book series "IFIP Advances in Information and Communication Technology" (IFIP AICT), Springer.

Chu, J., Anderson, J. L., Asche, F. and Tudur, L. (2010). Stakeholders' perceptions of aquaculture and implications for its future: a comparison of the U.S.A. and Norway. *Marine Resource Economics* 25, 61-76.

Economist (2003a). "The blue revolution: A new way to feed the world", *The Economist*, 7th August 2003.
http://www.economist.com/node/1974450

Economist (2003b). Fish farming: The promise of a blue revolution, *The Economist*, 7th August 2003. http://www.economist.com/node/1974103

FAO. (2008). *The State of World Fisheries and Aquaculture 2008*. Rome. 176 pp.

FAO. (2012). *The State of World Fisheries and Aquaculture 2012*. Rome. 209 pp.

FAO/WHO (2011). Report of the Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption. Rome, Food and Agriculture Organization of the United Nations; Geneva, World Health Organization, 50 pp.

Forsberg, O.I. and Guttormsen, A.G. (2006). Modeling optimal dietary pigmentation strategies in farmed Atlantic salmon: Application of mixed-integer non-linear mathematical programming techniques. *Aquaculture* 261, 118-24.

Jensen, H.H. (2006). Changes in seafood consumer preference patterns and associated changes in risk exposure. *Marine Pollution Bulletin* 53, 591-8.

Kvaløy, O. and Tveterås, R. (2008). Cost structure and vertical integration between farming and processing. *Journal of Agricultural Economics* 59, 296-311.

Larsen, T.A. and Asche F. (2011). Contracts in the salmon aquaculture industry: an analysis of Norwegian salmon exports. *Marine Resource Economics* 26, 141-49.

Nesheim, M.C. and Yaktine, A.L. (Eds.). (2007). Seafood Choices: Balancing Benefits and Risks. Institute of Medicine of the National Academy. Washington, D.C., National Academy of Sciences Press. 722 pp.

Nilsen, O.B. (2010). Learning-by-doing or technical technological leapfrogging: production frontiers and efficiency measurement in Norwegian salmon aquaculture. *Aquaculture Economics and Management* 14, 97-119.

Smith, M.D. , Roheim, C.A., Crowder, L.B., Halpern, B.S., Turnipseed, M., Anderson, J.L., Asche, F., Bourillón, L., Guttormsen, A.G., Kahn, A., Liguori, L.A., McNevin, A., O'Connor, M., Squires, D., Tyedemers, P., Brownstein, C., Carden, K., Klinger, D., Sagarin, R. and Selkoe, K.A. (2010a). Sustainability and global seafood. *Science* 327, 784-786.

Smith, M.D, Asche, F., Guttormsen, A.G. and Wiener, J.B. (2010b). Genetically modified salmon and full impact assessment. *Science* 330, 1052-1053.

Tacon, A.G.J. and Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture* 285, 146-158.

Tveterås, R. (1999). Production risk and productivity growth: some findings for Norwegian salmon aquaculture *Journal of Productivity Analysis* 12(2), 161-179.

Tveterås, R. (2002). Industrial agglomeration and production costs in Norwegian aquaculture. *Marine Resource Economics* 17(1), 1-22.

Tveterås, R. and Battese, G.E. (2006). Agglomeration externalities, productivity and technical inefficiency. *Journal of Regional Science* 46, 605-625.

Tveterås, R. (2012). Production: global fish review. *Global Aquaculture Advocate* 15(1), 9-10.

Tveterås, S. (2002). Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industry growth. *Marine Resource Economics* 17(1), 121-32.

Tveterås, S. and Tveterås R. (2010). The global competition for wild fish resources between livestock and aquaculture. *Journal of Agricultural Economics* 61, 381-97.

Valderrama, D. and Anderson J.L. (2010). Market Interactions between aquaculture and common-property fisheries: recent evidence from the Bristol Bay sockeye salmon fishery in Alaska. *Journal of Environmental Economics and Management* 59, 115-28.

Appendix A: Production of all aquaculture sector observations 1950-2010 (in metric tonnes)

	No. of sectors	Average sector	Sector std. dev.	Smallest sector (min)	Largest sector (max)
World	48 339	23 357	167 497	0	4 418 010
World regions:					
Africa	5 397	2 086	15 511	0	527 049
Asia	20 541	48 926	253 313	0	4 418 010
Europe	12 937	5 232	26 760	0	927 876
Latin America	5 767	3 948	19 610	0	388 048
North America	1 567	12 202	33 209	0	300 056
Oceania	2 130	1 528	7 694	0	100 100
Developed vs developing countries:					
Developed	17 026	8 448	35 577	0	927 876
Developing	31 313	31 464	205 999	0	4 418 010
China	1 803	370 158	736 897	0	4 418 010
Norway	269	40 705	136 101	0	927 876

HAV21 – An R&D Strategy for a Marine Nation of Substance

Liv Monica Stubholt
Kvaerner ASA, Senior Vice-President, Strategy

Norway has already a leading position globally as a nation with a substantial marine knowledge base and strong ocean-related industries. Nevertheless, there is still great potential for development. In 2011, the Norwegian government appointed a committee with the task of giving advice on national marine science strategy. The commissioned report was submitted in late 2012.

The main message is that it is essential for Norway to continue to invest in this sector. The report also recommends targeted and integrated marine research activities to support the development.

The HAV21 strategy report sets out important priorities that will help enable Norway to achieve the country's strategic, industrial and political objectives for the marine sector, while recognising and embracing the paramount requirement of all coastal states: to base their ocean-orientated activities on an uncompromising premise of sustainability.

This article briefly describes the background of HAV21 and sets out its main recommendations. The role of knowledge as a means in setting the course for business and societal development is discussed.

HAV21 – background and recommendations

Norway has a strong global position in marine research, ocean management and marine industries. The shipping, seafood and offshore industries form Norway's most valuable and complete business clusters. The common denominator for these industries is the ocean. Moreover, Norway has a modern, operational and well-functioning public management regime for marine activities, including new and quite sophisticated integrated management plans for certain sectors of the ocean along the Norwegian coast – aiming to cover all key sea areas within the near future. It makes a lot of sense for Norway to continue investing in the marine sector – a sector in which it excels.

The HAV21 strategy committee was appointed in autumn 2011 by the Ministry of Fisheries and Coastal Affairs on behalf of the Government to draw up a proposal for an integrated research strategy for the overall field of marine science. The committee's mandate was to identify key knowledge areas worth exploring and to recommend how these priority areas could be developed. Knowledge, however, does not harvest its full potential unless placed in relevant context. Thus, the HAV21 strategy report also addresses questions pertaining to what needs to be done to achieve optimal research and development activities from investments in marine research. The report identifies major knowledge needs and points out that both the private and the public sectors need to boost their investments into research and development if joint ambitions are to be achieved and opportunities fully realised.

Historically, the ocean has played a key role in Norway's development as a nation, and it will continue to do so in the future. The ocean and its resources are being used increasingly intensively for a variety of purposes and, more and more, political, social, industrial and resource management-related objectives and interests are competing with one another. Thus, the use and conservation of the benefits provided by marine ecosystems must be weighed against each other to balance the interests of the many stakeholders and of society at large. The question is how. More knowledge will not only help us to find the scientific answers and opportunities. It will also help us succeed in performing that very complex balancing act.

Current and anticipated climate change will lead to major changes in the functioning and productivity of marine ecosystems in the future. As the activities in coastal and marine areas increase, so does the complexity of research questions relating to the use and conservation of ecosystems. While a longstanding culture of dialogue between stakeholders is practised in many of the marine sector's arenas, there is still room for improvement. The more effective the consensus and/or co-operation achieved, the greater the gains for the marine sector and society at large. The HAV21 strategy committee recommends expanding the interdisciplinary, cross-sectorial approach to research, management and industrial development.

The overall recommendations set out in the HAV21 strategy report are based on stand-alone reports submitted by the four independently-working groups appointed to support the strategy committee with input in the areas of *management (including basic research), fisheries, aquaculture* and *food*.

The HAV21 strategy committee has based its recommendations on the assumption that the current significant investment trend in marine research will continue to be a national priority and will be followed up by all of the relevant ministries: the Ministry of Fisheries and Coastal Affairs, the Ministry of Education and Research, the Ministry of the Environment, the Ministry of Foreign Affairs, the Ministry of Trade and Industry, the Ministry of Petroleum and Energy, the Ministry of Agriculture and Food, and the Ministry of Health and Care Services.

The HAV21 strategy committee's recommendations

Funding of research and development

Norway takes a broad-based approach to knowledge building and conducts a considerable amount of marine research and development. Nevertheless, new knowledge is needed in order to further develop marine industrial activities and management, and both the public and the private sectors need to step up investment in marine research and development significantly. The strategy committee recommends that consideration be given to amending current regulations in order to increase private sector funding by raising the proportion of the overall fee levied on seafood exports (which is comprised of a market fee and a research fee) that is allocated to R&D, or, alternatively, by raising the overall export fee.

Legal perspectives, management and use

Increased ocean activities will challenge the regulatory regime as new issues are raised and interests overlap or clash. Research-based knowledge must be included in the basis for national and international legislation and regulations on the use and conservation of marine resources, industrial activity and traffic in coastal and marine areas. Many Norwegian acts and regulations are intertwined and have elements in common with international regulations and treaties. Knowledge and to some extent harmonisation will improve the efficiency of decision-making processes. The strategy committee recommends strengthening research on the legal perspectives of marine issues, and also recommends setting up an interdisciplinary research project on future principles for and organisation of marine and coastal management.

Knowledge about the ecosystem

Clean, thriving oceans are fundamental to the marine industries. The strategy committee recommends funding long-term research to obtain better understanding of marine life and processes, with a focus on current drivers of change: impacts of climate change, acidification, harvesting of biological and other resources, pollution and other anthropogenic activity – including the impact these developments have on each other.

Norway has a long track record of using advanced marine infrastructure, research vessels, research stations, buoys, satellites, seabed installations, planes and models for gaining insight into, and monitoring, the ecosystem. The strategy committee recommends continued investment in infrastructure to ensure efficient data collection, effective monitoring and optimal prediction at various time scales.

The Arctic and northern areas

The geopolitical, security policy and strategic significance of the Arctic and northern areas is growing. Success in managing and using resources in these areas, balancing considerations relating to local communities and understanding the role of this region for global climate development, will require knowledge from technology and the natural sciences, social sciences and the humanities. Marine research in the Arctic and northern areas must be intensified in keeping with the Government's High North Strategy and the general consensus in Norway to use and protect Norwegian interests in these areas, at the same time ensuring that sustainability guides all activities.

Harvesting and cultivating new marine raw materials

Cultivation of marine raw materials for use in fish feed, energy production and for the purpose of human consumption may become a new, important

An aquaculture plant in northern Norway. Photo: Norwegian Seafood Council/Johan Wildhagen.

growth industry along the Norwegian coastline, in part due to the projected scarcity of traditional marine feed ingredients for use in the aquaculture industry. The strategy committee recommends research on potential opportunities and knowledge relating to new marine raw materials.

Fish health and sustainable, safe and healthy seafood

Reducing the incidence of fish disease is essential to maintaining the profitability, sustainability and good reputation of the aquaculture industry. Product-conscious consumer groups are demanding that seafood is produced sustainably under healthy conditions and that the quality of the seafood can be documented objectively and reliably by public authorities with the help of research-based systems and methods. The establishment of effective zones or production areas is a key measure in this context.

Documenting the relationship between seafood consumption and human health is important both for the Norwegian market and for marketing seafood abroad. The strategy committee recommends continuing high-calibre research on fish health and sustainable seafood production, as well as investing in research to document the sustainability and quality of the seafood produced.

Food and markets

Norway already exports seafood on a large scale, but there is still tremendous potential for expansion. Further development is dependent on knowledge about markets and consumers. The strategy committee recommends building a market research community of high international standard to better understand the impact of changes in existing markets and the challenges posed by new ones. The objective is to develop better knowledge about product development, competitive conditions, marketing and distribution channels, brand-building and changes in consumer behaviour with the objective of not only producing quality seafood in Norway but also marketing it successfully.

Technology

New technology is essential to promoting thriving coastal communities and addressing new and existing environmental challenges. Innovations in technology will also provide a basis for launching new and further developing existing marine industrial activities. The strategy committee recommends investing in technology for the fisheries and aquaculture industries that draws on expertise in technology development from the maritime and offshore sectors incorporating components from biotechnology, nanotechnology/materials technology, and information technology.

Interdisciplinary research

Solving problems and making the most of opportunities is growing more and more complex and is increasingly contingent on knowledge harvested from many fields. R&D activities naturally tend to delve into specialities to conquer new frontiers and this is a strong quality that will bring results. The strategy committee nevertheless recommends that research projects are organised to include interdisciplinary and cross-sectorial dimensions to ensure that solutions found across sectors may also be caught and that co-operation between groups of different scientists may address new challenges relating to management and industrial activity.

Education and training programmes

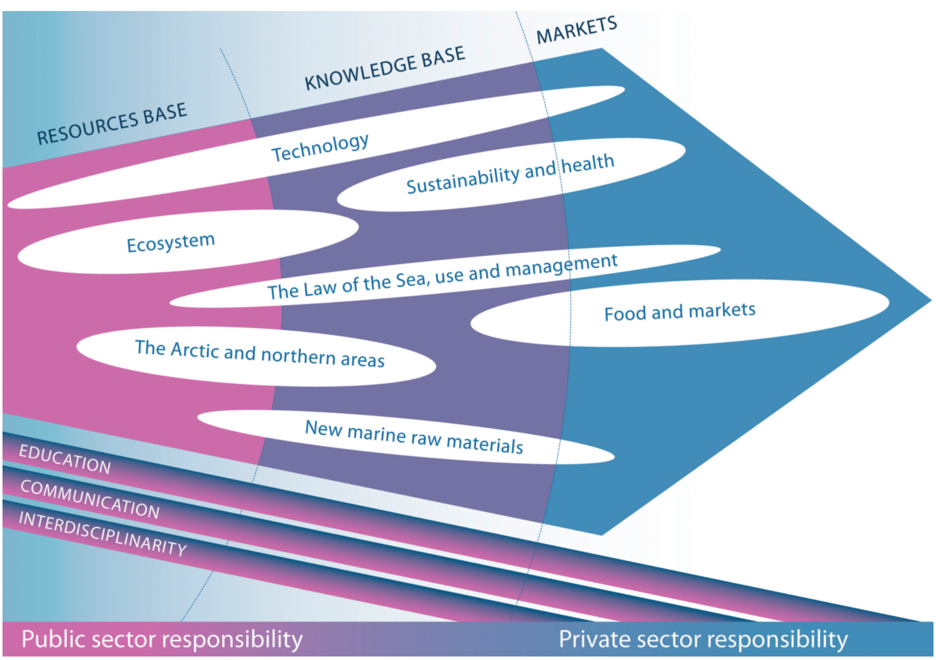
Meeting tomorrow's challenges will require a great deal on the part of industry and the research community, and competition for the most highly qualified personnel is tough. Research careers in the marine sector must be made more attractive. Permanent researcher positions must be established at universities and university colleges, with particular focus on post-doctoral positions to create greater stability for younger researchers. The independent research institutes should become more involved in education and training programmes.

Communication activities

Research results must be communicated actively to the public administration, trade and industry and public at large, as well as within the research community itself. The strategy committee recommends that research projects systematically set aside time and resources for communication activities to ensure that the research being conducted is relevant and the results are disseminated and put to use. This will not only contribute to the objective of the R&D activities but will support and strengthen the legitimacy of continued spending on R&D and contribute to recruiting new talents to science.

Knowledge as a vital means in setting the course for business and societal development

Knowledge is playing an ever-increasing role in setting the course for business and societal development. Developing and developed countries



The HAV21 strategy committee's overall recommendations. Illustration: HAV21.

alike make strides to attract competent people from abroad to bolster their own competence and enhance social and business development.

For a country like Norway, although being a highly developed country, it is clearly of great strategic importance to decide on which topics we will focus our research. For a leading international maritime country with an ocean area seven times larger than our land area and with rich resources such as fish and petroleum, research and development pertaining to fjords, seas and oceans is of paramount importance. Norway has been pro-active in developing not only ocean-related business activities but also sustainable management of resources and ocean areas. Norway has to some extent inspired the development of new international laws and regulations in this area and we experience eager international interest in the ocean management tools developed in this country during the last few years.

There is also a mounting national and international interest in the High North, for various reasons. Climate change is opening up new business opportunities in the areas of fishing, petroleum exploitation and shipping. The international community is showing increased interest in taking part in this development.

However, opportunities are also – as always – accompanied by challenges. In the High North all maritime logistics, such as shipping and oil production, pose environmental challenges. One example is oil spills in icy waters. Seismic activities have an impact on marine life, and managing fish stocks and fishing rights are challenged by increasing ocean temperatures and changes in migration patterns.

For the above reasons, and more may be added, it is important that Norway consistently pursues research and development, from basic research to innovation, in the fields of natural science, applied science, technology, societal research and the humanities, enabling us to protect and utilise our marine areas and harvest our natural resources in a sustainable manner.

Being a small country with large ocean areas the only efficient way to manage and use the oceans in a modern forward-looking way, is to base all decisions on sound and accepted knowledge. A large part of this knowledge must be internationally accessible, but in some cases proprietary when it is necessary to protect national interests.

A core message in the HAV21 strategy report is that knowledge developed within the frame of a dialogue between partners more readily acquires legitimacy and quality, thereby creating a common platform for agreeing on recommendations and prioritisations. Therefore, knowledge becomes a tool for setting directions.

The strategy committee concludes that the best safeguard for a strong marine science base is the close co-operation between all stakeholders to ensure context, communication of objectives and results, as well as the continued political and societal support for the strong link between marine sciences and the substantial values that our proximity to the sea creates for Norway.

About the authors

Lisbeth Berg-Hansen was appointed Minister of Fisheries and Coastal Affairs in 2009. She is representing the Labour Party. From 2002 to 2008 she was a member of the Executive Committee and Board of Directors of the Confederation of Norwegian Enterprise, serving as Vice-President from 2004 to 2008. In 2000-2001 she was State Secretary at the Office of the Prime Minister (Stoltenberg I Government) and in 1992-1996 she was Political Adviser for the Ministry of Fisheries. She has been Deputy Chair of the local municipality council in her home community Bindal for eight years, and has also had other political posts at local and regional levels. Mrs Berg-Hansen has held various positions within the Norwegian Seafood industry, and has had board positions both within and outside the seafood sector. Mrs Berg-Hansen was educated as a dental assistant.

Karl Andreas Almås is President and CEO of SINTEF Fisheries and Aquaculture. MSc in biochemical engineering (1976) and PhD (1982). He has a background as research scientist from the Norwegian University of Science and Technology (NTNU), from the Department of Food Science, University of Wisconsin, Madison, and as Research Director at the Norwegian Institute of Fisheries Technology Research, Tromsø. During most of his scientific career he has been focusing on fish processing technology and industrial marine biotechnology. Together with Norsk Hydro he was involved (1986-1990) in the development of new marine biotechnology and bioingredient companies. He came to SINTEF in 1991 from the industry in Tromsø, first as a director of SINTEF Chemistry and later (1999) as the first President of SINTEF Fisheries and Aquaculture when this institute was established. Board member and chairman of various industrial companies and scientific committees. Elected member and Vice-President of The Norwegian Academy of Technological Sciences.

Yngvar Olsen is Professor at the Norwegian University of Science and Technology (NTNU), Department of Biology, Trondhjem Biological Station (since 1995). From 2006 he has acted as Director of the Strategic Marine Focus Area at NTNU. He has been a senior scientist at SINTEF Aquaculture. He has almost 30 years' experience within the main research fields of aquaculture and marine plankton, including live feed technology for marine fish larvae, lipid nutrition and first feeding, ecology and nutrition of marine phyto- and zooplankton, nutrient cycling, coastal eutrophication, environmental interactions of aquaculture, and integrated multi-trophic aquaculture. He has published more than 120 papers in international peer-reviewed journals and given several hundred presentations at conferences and meetings. Yngvar Olsen was a Vice-President of the World Aquaculture Society (WAS) in 2002 and a member of the Board of Directors 2003-06, and is currently the co-chair of the Thematic Area "Aquaculture Interaction with the Environment" in the European Aquaculture Technology and Innovation Platform (EATiP).

Stig W. Omholt is Research Professor at the Norwegian University of Life Sciences (UMB) at Ås. He was until recently Director of the Centre for Integrative Genetics at UMB and Kristine Bonnevie Professor at the Centre for Ecological and Evolutionary Synthesis, a centre of excellence at the University of Oslo. He is now also Director of the newly established programme on biotechnology at the Norwegian University of Science and Technology (NTNU) in Trondheim, named NTNU Biotechnology - the Confluence of Life Sciences, Mathematical Sciences and Engineering. Stig Omholt has worked on a wide range of research themes over the years, including sociobiology, biogerontology, mathematical modelling of brain physiology, the mathematics of tanning, linking genetics theory with systems dynamics to establish a real quantitative genetics theory, experimental evolution of single-celled eukaryotes, linking genetics to cardiovascular modelling, the etiology of hypertension, and the ultimate reasons for why the salmon possesses pink flesh. Stig Omholt played a key role in the establishment as well as the funding of the Atlantic Salmon Genome Sequencing Project.

Arne B. Gjuvsland is a researcher at the Centre for Integrative Genetics at the Norwegian University of Life Sciences (UMB) at Ås, working with causally cohesive genotype-phenotype models and virtual genomes. The overall goal of his research is to understand how biological systems shape the genotype-phenotype map. In his PhD (2007) work he developed conceptual frameworks and simulation software for linking quantitative genetics and gene regulatory networks. He is currently involved in the Virtual Physiological Rat Project, funded by the U.S. National Institutes of Health. This project aims to build validated computer models of the integrated cardiovascular function in the rat and account for genetic variation across rat strains and physiological response to diet. He is also working on a project (funded by the Research Council of Norway) on high-throughput experimental evolution providing molecular and systemic understanding of the adaptive potential of yeast.

Jon Olav Vik is a researcher at the Centre for Integrative Genetics at the Norwegian University of Life Sciences (UMB) at Ås, working on causally cohesive genotype-phenotype modelling and the analysis and comparison of virtual physiology models. Prior to this, he studied the effects of climate change on population dynamics at the Centre for Ecological and Evolutionary Synthesis at the University of Oslo. He did his PhD (2002) in theoretical ecology from the Norwegian University of Life Sciences, studying how alternative stable size distributions can arise from size-dependent predation and density-dependent growth. His eclectic skill set includes dynamical systems modelling, optimisation, computing and statistics, coupled with wide experience from collaboration on particular biological systems. He enjoys facilitating the productive interplay of experimental and field biologists, statisticians and computational scientists, and is currently involved in an international effort towards infrastructure for systems biology in Europe (ISBE).

Ragnar Tveterås is Professor at the University of Stavanger (UiS) Business School and Head of the Centre for Innovation Research, a joint research centre for UiS and the International Research Institute of Stavanger (IRIS). He has an MSc in economics from the University of Bergen (1993) and dr. oecon (PhD) from the Norwegian School of Economics and Business Administration (NHH) (1998). Tveterås has since the 1990s been involved in research on industrial economics, focused mainly on the seafood and petroleum sectors. He is particularly concerned with the conditions for growth and investments in these sectors, through contributions to increasing the research-based knowledge on production, distribution and markets. In addition to scientific publishing he promotes the dissemination of research results to decision makers in the private and public sectors, as well as to a broader audience through presentations at conferences and articles in the trade press and other media. He is in continuous dialogue with private and public sector decision makers. Tveterås has been adviser and collaborated with e.g. Innovation Norway, Norwegian Seafood Council, Norwegian Petroleum Directorate, BluePlanet, Marine Harvest, Nutreco Skretting, FAO, OECD and Global Aquaculture Alliance.

Liv Monica Stubholt is Senior Vice-President Strategy and Communication at Kværner, which she joined in April 2012. Since 2009 Ms Stubholt has held the positions of Investment Director in Aker ASA, CEO and President of Aker Seafoods ASA, and CEO of Aker Clean Carbon AS. Ms Stubholt (Senterpartiet) served in the Stoltenberg I Government as Deputy Minister of Foreign Affairs (2005-2007) and Deputy Minister of Petroleum and Energy (2007-2009). Ms Stubholt graduated in law at the University of Oslo (1987) and has practiced as a lawyer, partner and adviser in the first part of her career (1987-2005). She serves on the Board of Directors of Norsk Hydro. She is a member of Innovation Norway's newly established strategic council for IN's foreign activities. She is on the advisory boards of the International Crisis Group and the Fridtjof Nansen Institute and is a former leader of the strategy group for Hav21.

John Grue is Professor of Hydrodynamics at the Department of Mathematics, University of Oslo since 1994. His research field is marine hydrodynamics and mathematical and experimental wave theory, and he has worked in the intersection between theoretical and industrial applications. He has built up an experimental wave laboratory at the University and has led several research projects funded by the Research Council. He has been a board member of the Norwegian Academy of Science and Letters (DNVA) (2007-12) and Chair of the Mathematics and Natural Sciences Division of DNVA in 2008, 2010 and 2012. He represents Norway in the General Assembly of the International Union of Theoretical and Applied Mechanics (www.iutam.net) and is currently Chair of the International Workshop on Water Waves and Floating Bodies (www.iwwwfb.org). He is guest professor at Harbin Engineering University in China, elected member of the Norwegian Academy of Science and Letters and the Norwegian Academy of Technological Sciences.