UNIVERSITY OF GOTHENBURG
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Master Degree Project in Innovation and Industrial Management

Innovating Out of the Fishmeal Trap

A case study on how niche conditions in the Norwegian aquafeed sector led to the development of a sustainable technology with global potential

Jonathan Moy de Vitry

Supervisor: Johan Brink
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INNOVATING OUT OF THE FISHMEAL TRAP

By Jonathan Moy de Vitry

School of Business, Economics and Law, University of Gothenburg, Vasagatan 1, P.O. Box 600, SE 405 30 Gothenburg, Sweden

Contact: jon.a.mdv@gmail.com

Abstract

As trends in population growth, resource scarcity, and global warming converge, global food security is becoming a pressing issue. To address this challenge, agricultural systems will have to transition towards more efficient and sustainable production regimes through the generation and diffusion of new technologies. The role of governance in catalyzing this change has long been a topic of research and debate. In this thesis, the author borrows from the concepts of "niches" and functional analysis to evaluate the role of governance and other factors in pioneering "Dynamic Formulation" technology for salmon within the Norwegian aquaculture sector. This technology was used to substitute expensive fishmeal, extracted from declining stocks of wild fish, with more economic and sustainable feed ingredients. It was found that the "niche" conditions, which facilitated this technological emergence, were only indirectly attributable to government policy. Instead, long-term price incentives, industry dynamics, and attributes of the technology itself were major drivers behind this innovation. This thesis contributes to multi-level and innovation system literature with a hybrid framework applied to a previously unstudied case and encourages discussion about the role of governance in optimizing an already functional "niche".

Keywords: Innovation systems, production regimes, sustainable innovation, multi-level perspective, technological change; dynamic formulation technology

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Acronyms

DF – Dynamic Formulation
NASS – Norwegian Aquafeed Sectoral System
SSPI – Sectoral System of Production and Innovation
TIS – Technological Innovation System
FCR – Feed Conversion Rate
FMFO – Fish Meal & Fish Oil
FIFO – Fish In –Fish Out Ratio
GMO – Genetically Modified Organisms
EU – European Union
NOK –Norwegian Krone

1. Introduction

“ Aquaculture offers an increasingly attractive solution to meeting food needs. Aquaculture is already the fastest growing animal food producing sector, but the potential for further expansion is great. Nothing I have said so far calls upon this industry to change direction, but I have asked you to accelerate progress.”

Kofi Annan, Former Secretary General of the UN, speaking to members of the aquaculture industry at the Aquavision conference in 2011

As trends in population growth, resource scarcity, and global warming converge into a Malthusian catastrophe, food security is becoming a critical issue in many parts of the world. To address this challenge, food production systems will have to transition towards more efficient and sustainable production regimes through the generation and diffusion of new technologies. While countless obstacles present themselves in this endeavor, two major impediments will need to be addressed if the world is to avoid widespread famine. First of all, efforts to develop sustainable technologies, like most forms of innovation can be time-consuming, costly, and potentially fruitless. Incentives, resources and capabilities to undertake these important activities are not always present in the right proportions in agriculture sectors. Secondly, many environmentally viable innovations face stiff competition from incumbent technologies deeply embedded in established networks of actors and behaviors. This phenomenon serves as a barrier to their development and diffusion and has been known in the past to effectively “kill” promising new technologies. Thus, there is a need to understand the actions that can be taken to foster the development of sustainable technologies and encourage their propensity to displace or reconfigure incumbent production regimes to be more in line with food security needs.

One area of research, *innovation systems,* looks at the success or failure of technologies as the result of commercial and non-commercial interactions between networks of actors under certain institutional settings. Innovation systems frameworks can be used to analyze a country's ability to generate innovation i.e.. national innovation systems (NIS), an industry's ability to develop and utilize technology i.e., sectoral systems of innovation and production (SSPI), or even a certain technology's ability to progress based on its related actors i.e., technological innovation systems (TIS). In the case of a technological innovation system, the capacity of a series of actors to perpetuate innovation can be described as its prime functionality. Several papers have been published on the subject of TIS functionality regarding sustainable technologies with the ultimate aim of understanding how this capacity can be nurtured.

Another school of thought, the multi-level framework, views technological change as an interplay between different socio-technical layers exhibiting heterogeneous selectionary forces. Radically different technologies, protected from pressures present in other layers, mature in "niches" before emerging to compete with larger production systems, eventually becoming incumbents themselves. Built on this framework is a field of studies called *niche management,* which focuses on the role of governance in creating artificial niches with the capacity to generate innovations with environmentally and/or socially desirable attributes. However, niches may also emerge from a convergence of extraneous factors.

In this paper, the author hopes to combine both TIS and niche management perspectives through a case study of a niche agricultural industry in which a sustainable innovation was pioneered. The Norwegian aquafeed sectoral system (NASS) was chosen for this purpose because of its remarkably successful role in developing Dynamic Formulation (DF) feeds, a technology that allows for the substitution of fishmeal, extracted from declining stocks of wild fish, with more economic and sustainable ingredients.

This investigation is linked to the discussion on the respective roles of firms, society, and governance in driving sustainable innovation. Classical economic theory views the development and adoption of sustainable technologies as suffering from market failures that must be remedied through government policy measures, such as subsidies and taxes. These measures have often been opposed by industrial actors on the basis that they impose unjustifiable costs and erode competitiveness, especially in international markets. Some economists have refuted these claims, arguing that these interventions, especially if well-designed, could actually reinforce long-term industry positions by incentivizing innovation. This perspective is aligned with the Dunphy's phase model, which sees sustainable innovation within firms as economically viable without interventions, especially in industries where resource efficiency is linked to competitiveness.

On a more general note, this case also relates to how industries and their constituents respond to systemic threats from issues like resource scarcity. Can industries effectively save themselves through innovation or do they require direct intervention from governance? If not, what industry dynamics facilitate this ability?

Based on 20 interviews with members from the industry as well as secondary data sources, the empirical section of this case describes NASS dynamics, and explores the development of DF technology within it. Rather than trying to analyze the case using a pure innovation systems approach, this paper applies functionality tools, designed to evaluate TISs, to the niche construct from the multi-level theory. This hybrid framework allows for an in-depth exploration of niche innovative capabilities and contributes to the discussions introduced above.

Research Question and Report Structure

While the main focus of this case was described above, several topics need further clarification as sub questions. The technology at the heart of this case, for example, lacked a name and concrete description in literature and needed to be defined. Furthermore, the *niche conditions* present in the NASS need to be clarified based on their divergence from global norms. Then a link must be drawn between these niche conditions and the overall technological progress achieved within it through functionality. To add theoretical value to this case, these niche conditions can be parsed by their emergence as the result of governance. With these considerations in mind, the research question and sub-questions present themselves thus:

Can niche conditions within a sectoral system of production and innovation generate sustainable technology without direct government intervention?

1. What is Dynamic Formulation technology and what is its importance to the economic and environmental viability of the Norwegian aquaculture sector?
2. Can the Norwegian aquafeed subsector (NASS) be considered a niche?
3. How have these niche conditions generated the functionality necessary to develop DF technology?
4. To what extent have these niche conditions and their functionality been influenced by governance and/or other factors?

2. Theoretical Framework

This section provides a brief overview of the frameworks and theories that will be used to explore the case.

Sustainability

Sustainability is an important concept with an imprecise definition that is heavily contextual. The WWF defines sustainability as “ improving the quality of human life while living within the carrying capacity of supporting eco-systems". Thus, sustainable development is described as balancing economic, environmental, and social goals. (IUCN 2006). This perspective evolves from the concept that the neglect of any of these three pillars will bring about long-term negative consequences, even if the timescale is multi-generational.

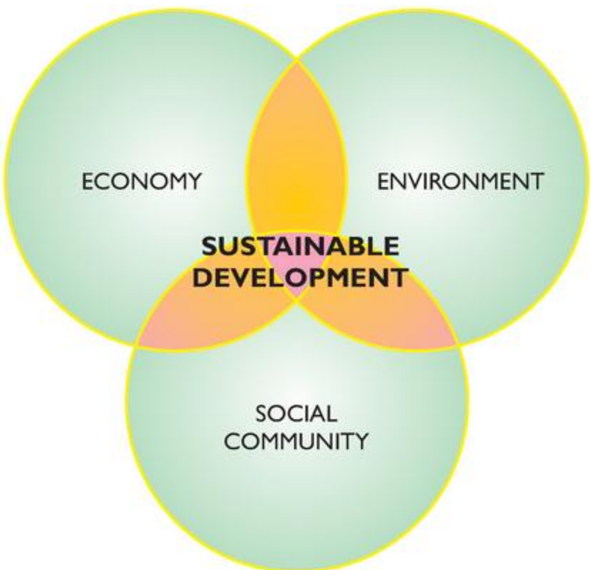


Fig 2.1 Sustainable development

However, it is extremely difficult to objectively quantify the sustainability of an society or enterprise. While there may be a multitude of metrics that can be seen as indicators of environmental or societal performance, it is difficult to assign a value to each one (ibid). Unlike financial profitability, there is no universally accepted "unit" of sustainability that can be tallied in a balance sheet. Is a ton of CO_2 emissions equivalent to the use of a kilo of pesticides? How does one weight these characteristics against one another? These questions, while while addressable, can never fully answered. So, in the context of this report, the term "sustainable" will be loosely defined as "producing net positive effects on the environment and society".

The Multi-Level Perspective

To elaborate on the description provided in the introduction, the Multi-Level Framework explores the phenomena of technological change by dissecting society and its technological systems into three distinct layers. These layers are characterized by agglomerations of technological use (Geels et Schot 2007), which behave in some ways like systems. Technological change occurs as interactions between elements in these layers, described as follows:

Socio-Technical Regimes

Patterns of technological use held in place both by stabilizing institutions, such as actor perceptions, and by physical artifacts, such as infrastructure. Regimes exist at a meso, or intermediate, level and compete with one another. Sociotechnical regimes closely resemble industries in that they consist of patterns of technological use that may align along a certain economic activity.

These regimes have also been described as sets of “rules”, or technological paradigms held by actors using these technologies.

Niches

These are protected micro-level spaces, or “incubation rooms”, where innovations can develop away from the evolutionary pressures shaping the socio-technical regimes. One example of this is the willingness of niche actors to pay higher costs in exchange for technological functionality specific to their needs (R. Hoogma 2002). Thus, these niches allow for a certain degree of underperformance in competitive dimensions valued at a meso level, which is characteristic of many radical innovations in their early stages (Dodgson, Gann et Salter 2008)

Niche conditions allow for technical specialization, which co-evolves with the development of community of actors dedicated to it. As this occurs, technological uncertainties are winnowed out and dominant designs emerge within the niche (F. Geels 2005).

These niches can be formed by converging market conditions, *market niches,* or can be artificially created by institutions. Research has been devoted to the topic of *niche* or *transition management* (Hoogma 1998) This has led to theories about how to actively pursue desirable results, usually with regards to sustainable technology, through active manipulation of niches.

Socio-Technical Landscape

The context for the configuration of the *socio-technical regimes*. Created by a set of factors and forces beyond the control of actors in the regimes, *socio-technical landscapes* shift or change according to the forces surrounding regimes, setting the stage for their destabilization or prosperity. The forces take many forms: political, environmental, social, and even technological.

Within the Multi-Level perspective, several patterns of technological change, or "pathways", can be identified as emerging from interactions between the different layers (Geels et Schot 2007)

Transformation

In response to moderate landscape pressure, socio-technical regimes shift their innovation activities to adapt their directions towards changing conditions. Since the selectionary pressures aren't strong enough to fully destabilizes the regimes, only influence them, some niche technologies that are symbiotic with incumbent technologies may find a way to re-direct regimes.

De-alignment and re-alignment

Following a major landscape shock, regimes are destabilized and may collapse. In the absence of functional regimes, multiple partially-developed niche innovations may fill the void left by incumbents, competing against one another. Competitive selection will eventually lead to the re-establishment of regimes, although in different configurations.

Reconfiguration

Instead of landscape shifts pressuring existing regimes, *reconfiguration* comes from niche technologies developing to the point where they offer clear economic advantages to incumbents. They are then adopted, step-by-step, gradually shifting the architecture of their host regime over time.

Technological substitution

This pathway is of most interest to our case, as it covers the displacement of incumbent technologies and actors by those emerging from a niche. As landscape pressures weaken incumbent regimes, the newly formed contexts from them at an advanced enough stage to compete directly with incumbents.

Innovation Systems

As opposed to the linear (and somewhat obsolete) step-by-step model of innovation, this approach uses evolutionary economic theory to describe innovation as an outcome of interactions between actors and networks in a system influenced by institutions. Actors can be firms, divisions of firms, universities, NGOs, and of course government authorities (Dodgson, Gann et Salter 2008).

Innovation systems are analytical constructs formed of networks of interacting actors embedded in a common institutional environment. These spaces can emerge from unique geographic, commercial, technological, and institutional linkages and therefore. Thus, several different types of *innovation systems* have been proposed in the literature corresponding to different units of analysis. Systems inevitably overlap, as national innovation systems often contain several technological systems and technological systems may span several sectoral systems, etc.

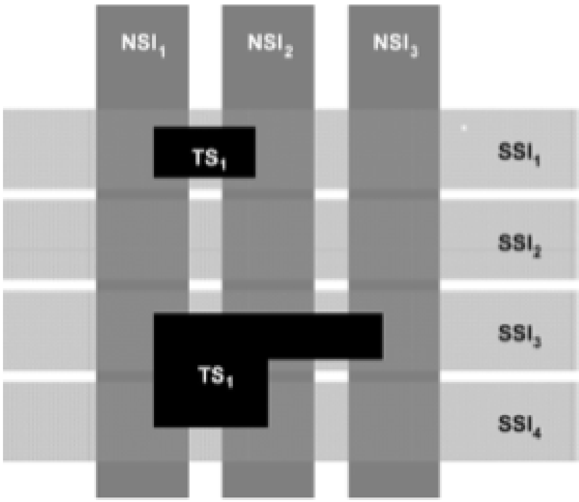


Figure 2.2 An illustrative example of overlaps between sectoral, national, and technological innovation systems (Truffer et Markard 2008)

National and Regional Innovation Systems

With theoretical origins in the 1800s, *national innovation systems* were the first innovation system recognized by academics seeking to understand the ability of certain nations to generate economic wealth through technological progress. Nations form useful units of analysis because they can exhibit distinct sets of institutional configurations that can enhance or hinder the ability of firms within them to engage in innovation.

Regional innovation systems focus more on networks, whose unique dynamics and shared institutional environment materialize from their geographic colocation. These geographic locations provide unique production factors valuable to innovative activity, and leverage their concentration. This proximity produces positive effects on innovation because of the greater knowledge feedback cycles allowed by the colocation of both the creation and application of knowledge. (Dodgson, Gann et Salter 2008)

Sectoral Systems of Production and Innovation

Another innovations system is presented by *Sectoral Systems of Production and Innovation* (SSPI) (Malerba 2002) which describe some innovation systems as emerging actors involved in innovation and production of a certain product sharing similar knowledge and learning processes, patterns of interaction, inputs and complementarities, thereby embedding them in a system. This concept therefore builds on the conventional definition of "industries", networks of actors engaging in similar sets of economic activities by including the innovation system generating the knowledge supporting this activity.

However, one particularity about the SSPI approach is that it does not attempt to impose boundaries on a system. Instead the SSPI is meant to study the dynamics and change in patterns of production in an industry. Seven shared characteristics that can be used to define a sectoral system have been identified, namely:

1. *Products*
2. *Agents*
3. *Knowledge and Learning Processes*
4. *Basic Technologies, Inputs, Demand and the Related Links and Complementarities*
5. Mechanisms of Interaction (Intra- and Extra-firm)
6. Processes of Competition and Selection
7. Institutions

Technological Innovation Systems

At the intersection of innovation systems and multi-level framework, we have the concept of the Technological Innovation System (TIS), a tool focused on understanding the development, diffusion and use of a new technology based on the actors that engage in its development and utilization (Truffer et Markard 2008). A TIS represents, more or less comprehensively, the network of actors contributing to a technology's evolution through patterns of activity known as functions.

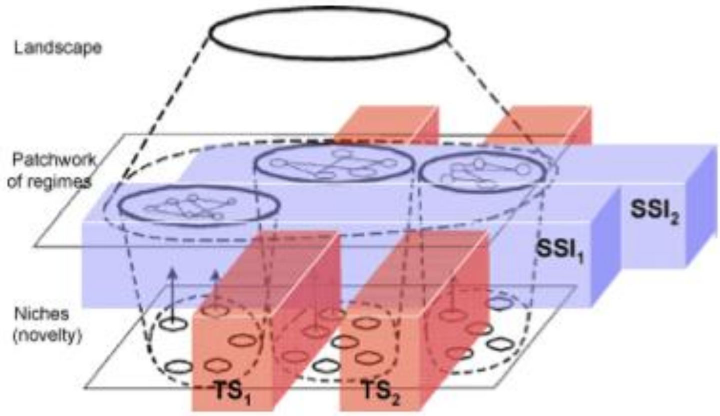


Fig 2.3 Innovation Systems and the multi-level perspective (Truffer et Markard 2008)

The term "network", however, is a bit misleading because there may not be any interactions whatsoever between many of the actors, especially if the TIS is in its early stages. A TIS may be a sub-system of larger technological systems if its range of application is unique to it or may span across several industries. (Truffer et Markard 2008) sets the minimum conditions for the basis of a TIS as including:

A. A variety of heterogeneous actors undertaking innovative activities in a certain technological field;
B. A division of labor with regards to innovative activities, in other words distribution of elements from the "innovation value chain" across several actors;
C. Unique institutions emergent from activities specific to the system actors; and,
D. Market transactions and multiple suppliers creating a competitive environment.

Technological innovation systems often lack geographic boundaries because of the distributed nature of knowledge development in globalized sectors. That said, technological innovation systems can have a focal point where knowledge creation and utilization are especially pronounced because of a convergence of favorable national, sectoral, and regional innovation systems. For example, the technological innovation system for mechanical watches involves almost the same set of actors as the Swiss watchmaking sectoral system, and could be considered superimposed on it.

Functions

Technical Innovation Systems can be analyzed in different ways, depending on the objective of the researcher. In this case the primary interest is in understanding the capacity of TIS to develop and diffuse a certain technology. The success of these activities has been linked to the functionality of these systems, or their ability to undertake the multitude of actions needed to overcome political, financial, technical, social obstacles.

These *functionalities* have been covered by various authors (Johnson 2002, Rickne 2000, Carlsson 2005, (Hekkert 2007) using slightly different taxonomy. Drawing on this work (Bergek, et al. 2008) proposes seven aggregated categories of functions. It is also worth noting that many of the functions complement and actively reinforce each others activities in a series of *virtuous cycles* (Hekkert 2007)

In this case study, the seven functions identified by Bergek will be used because they integrate not only economic and technological issues of development and diffusion but also social and political ones. Though this framework might not be mutually exclusive and comprehensively exhaustive, it was found to be actionable for the purpose of this case.

1. Knowledge Creation and Diffusion (KCD)

Technology is built on knowledge creation and learning processes of various forms. This function can be described in an innovation system as the sources of this knowledge (R&D departments, universities, research institutes, etc.), the nature of the knowledge created (scientific, technological, production, market, etc.), and the relative levels of activity and its diffusion patterns.

2. Influence on the Direction of the Search (IDS)

This function covers the range of factors pushing or pulling the direction of the technological focus of the TIS in various directions. For example, beliefs in the growth potential of a technology among actors or expected interventions by institutions could push R&D managers to allocate resources to a technological variant well-placed to take advantage of these shifts. A pull factor could come in the form of clearly articulated demand for technological application among potential customers.

3. Entrepreneurial Experimentation (EE)

Technological progress involves varying degrees of evolutionary selection to find viable solutions among nearly infinite technological configurations. This function represents the types of knowledge-building experimentation going on as a function of new actors with different perspectives entering the TIS. By empirically exploring the range of technological variants from these diverging perspectives, it is possible for the system to select configurations with a higher chance of socio-technical success.

4. Market Formation

Markets provide a commercial application for new technologies, so their creation is quite important for the health of an innovation system. The market formation progress of an innovation system can be assessed by determining what stage it is in (nursing, bridging, mature), and user characteristics, articulation of demand, as well as different institutional barriers and incentives.

5. Legitimation

To progress, technologies need social acceptance and to comply with relevant institutions. Influencing these is the function of legitimation whereby the viability of a technology becomes apparent to actors, especially those shaping the institutional environment. This function is especially important when an emerging technology must overcome an entrenched "incumbent" technology.

6. Resource Mobilization

Technologies require capital, both human and financial, to develop. This function expresses the ability of a TIS to marshal resources needed to support KCD and EE activities. These resources may come from financial institutions, firms with stakes in the development of the technology, or public institutions.

7. Development of Positive Externalities

This function regroups other technology-promoting effects of the innovation system that do not neatly fit in the others. These positive externalities include the formation of specialized labor pools and the creation of specialized actors.

Technology, Knowledge Creation and Innovation

Since we are building our analytical construct around a technology, it may be useful to define the term "technology", which includes the following:

1. The practical application of knowledge in a certain field;
2. The outcome of the application of knowledge; and
3. Knowledge specific to a certain field of endeavor.

These definitions do capture the essence of technology, but another description of it that is especially useful to our case is it being the collection of knowledge used to solve a certain problem. This knowledge can take on many different forms, for example scientific, technological, production, market, logistics and design and can be generated by many different sources including R&D activity, learning from application and imitation (Bergek, et al. 2008). Furthermore, its patterns of creation can be dependent on the nature of its goal (See Fig 2.4).

Mode 1	Mode 2
Problems set and solved in a context governed by academic community	Knowledge created in the context of application
Disciplinary	Transdisciplinary
Homogeneity of producers	Heterogeneity of producers; encouraged by information and communications technology
Hierarchical and continuing	Hetarchical and transient
Quality control through peer review	Socially and economically accountable and reflexive quality control
Emphasis on individual creativity	Creativity a group phenomenon

Fig 2.4 Modes of producing knowledge (Dodgson, Gann et Salter 2008)

For technologically driven-industries, such as the one in this case, R&D is a major source of knowledge creation and learning activity (Arnold, Guy et Dodgson 1992). Types of activity in R&D can vary widely, from basic research destined to explore the scientific principles underlying a certain technology to applied development activities creating usable artifacts from this knowledge.

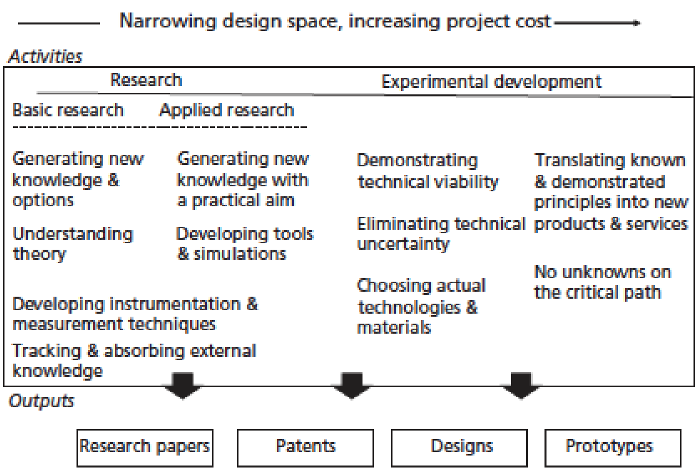


Fig 2.5 Types of R&D activity (Arnold, Guy et Dodgson 1992)

In this thesis, innovation is defined as the process and result of technological progress with a practical intent. Innovation can exhibit different characteristics. Depending on its degree of "differentness" and alignment with its socio-technical environment, an innovation can be more or less *radical* or *incremental.* An innovation can be a new product, service or process related to their production. Finally, an innovation can be *modular* (affecting only one component of a system or product) or *architectural* (modifying a fundamental design through a total reconfiguration of existing or new components).

Innovation Strategies and Appropriability

Perhaps the most important actors in our case SSPI are firms. The development and application of technologies for the purpose of production involves different actors in a cluster (Malerba 2002). Different tiers of the supply chain engage in significantly different innovative activities. While in some industries, knowledge creation and learning comes from R&D activity, in others it is a much more hands-on process involving suppliers (see Fig 2.6)

	Supplier-dominated	Scale-intensive	Information-intensive	Science-based	Specialized suppliers
Typical core sectors	Agriculture Services Traditional manufacturing	Bulk materials Automobiles Civil engineering	Finance Retailing Publishing Travel	Electronics Chemicals Drugs	Machinery Instruments Software
Main sources of technology	Suppliers Learning from production	Production, engineering Learning from Design offices Specialized suppliers	Software and systems departments Specialized suppliers	R & D Basic research	Design Advanced users
Main tasks of technology strategy	Use technology from elsewhere to strengthen other competitive advantages	Incremental integration of changes in complex systems Diffusion of best design and production practice	Design and operation of complex information processing systems Development of related products	Exploit basic science Development of related products Obtain complementary assets Redraw divisional boundaries	Monitor advanced user needs Integrate new technology incrementally

Fig 2.6 Innovation strategy (Pavitt 1984)

Even within a tier, firms may pursue a wide range of innovation strategies. Based their positioning within a sectoral system and firm-specific resources and capabilities, firms will implement different measures with regards to the development and commercialization of technology.

One major factor affecting innovation strategies within an industry are appropriability regimes, which affect the ability of an innovating agent to capture the returns on it. (Teece 1986) The strength of an appropriability regime can be linked to the nature of the technology itself, the complementary assets needed to use it, and the IPR institutions in place in the competitive field. In some cases, where IPRs can provide only limited protection from imitation, trade secrets may protect the diffusion of sensitive knowledge, although this is difficult to enforce.

3. Methodology

This section outlines the background of this case study and the methods used to collect and analyze data.

Background

The Norwegian case is important because innovation within agricultural industries facing resource scarcity and environmental issues will be essential for food security. However, under closer inspection, the sector didn't exhibit quite the characteristics that were anticipated. Therefore, the research strategy employed in this case can be best described as "emergent". While the initial intent of this case study was to map the range of technologies contributing to feed efficiency within the Norwegian aquaculture industry, thereby identifying the most influential ones, data collection proved to be difficult. Consequently the author adapted his methods accordingly to focus on the in-depth exploration of the development of one these technologies, for which the author has coined the term "Dynamic Formulation" (DF) technology.

Research Design and Data Collection

To capture the complex interactions surrounding innovation, a qualitative single case study format based on empirical data collected from interviews was used. This approach affords a level of flexibility in data collection and analysis that is lacking in quantitative methods. While much information on DF technology and the NASS was available in literature, many of the specific linkages between this data needed to clarified and developed. The author found that semi-structured interviews conducted with guides allowed for a nuanced and open-ended collection of empirics. Furthermore, these discussions served as a pedagogical tool for reinforcing tacit understanding of the particularities of the case in ways that literature couldn't.

Interview guides evolved along with the author's understanding of the case and shifting research objectives. Although each guide was individually scripted to match the background of the person being interviewed, certain key themes were present throughout all interviews and allowed for a degree of cross-validation.

The interviews took place over a series of 20 sessions with 18 different academics, researchers, and managers from the Norwegian aquaculture sector (Fig 3.1). The author made an effort to choose individuals from a range of background so as to include a diversity of historical, disciplinary and personal perspectives.

Organization	**Interviewees**
Research Institute / University	**7**
Aquafeed Firm	**5**
Other Firm	**4**
Government Organization	**1**
NGO	**1**

Fig 3.1 Interviewee backgrounds

All interviews were conducted by the author, via Skype or phone, with several individuals being interviewed more than once. The language of interview was English, which was spoken fluently by every participant. Sessions lasted between 15 to 90 minutes, with the average length of around 45 minutes. Seventeen of the interviews were recorded, while the contents other three were transcribed in notes.

Data Analysis

The analysis of this case rests on a collection of empirical and secondary data from articles, reports, and databases. Using an approach inspired by grounded theory, interview recordings were reviewed with the purpose of identifying recurrent themes and facts. This information was captured and organized using graphical "mind-mapping" software in an iterative process throughout the data collection phase. In cases where interviewee statements did not match, the author sought to clarify these inconsistencies through further interviews or secondary data sources. For precise numerical figures, the author has referred to secondary sources.

Research Quality and Limitations

Qualitative research inherently has some degree of researcher bias. The author was conscious of this and tried to limit interpretation of empirical data to the analysis section.

The author considers the greatest limitation of this case study to be the geographic scope of its empirics. All of the interviewees were members of the

Norwegian sectoral system, which could impose a national bias on their perspectives. That said, the author did try to test the statements made in these interviews with secondary data and found no evidence of systemic bias.

4. Norwegian Aquaculture, FMFO, and Innovation

This section defines the role of aquaculture in promoting food security, describes the Norwegian aquaculture sectoral system, and discusses the risks of its dependence on fish-derived inputs for aquafeed, primarily fish meal and fish oil

Aquaculture and Food Security

From a technical point of view, plant-based diets are more efficient than meat at meeting basic nutritional needs of humans. Humans have no specific requirements for meat itself but only for the amino acids and other micro nutrients it contains. Unfortunately, humans have a strong behavioral affinity for meat that we will gladly pay to satisfy, a tendency reflected in the increasing consumption of meat in emerging economies. Because of strong path dependency in systems of meat production and consumption, in absence of any dramatic legal or social shifts, this trend will probably continue as long as it is economically feasible to do so. So, while it may be of long-term interest to reduce meat consumption, short- and medium-term efforts to promote food security should focus on more sustainable and efficient meat production (FAO 2006).

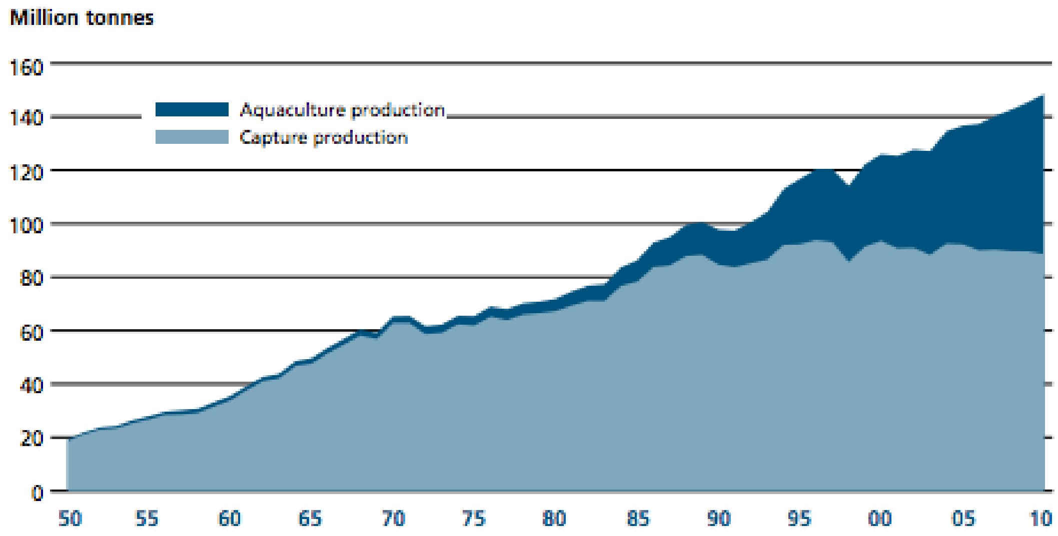
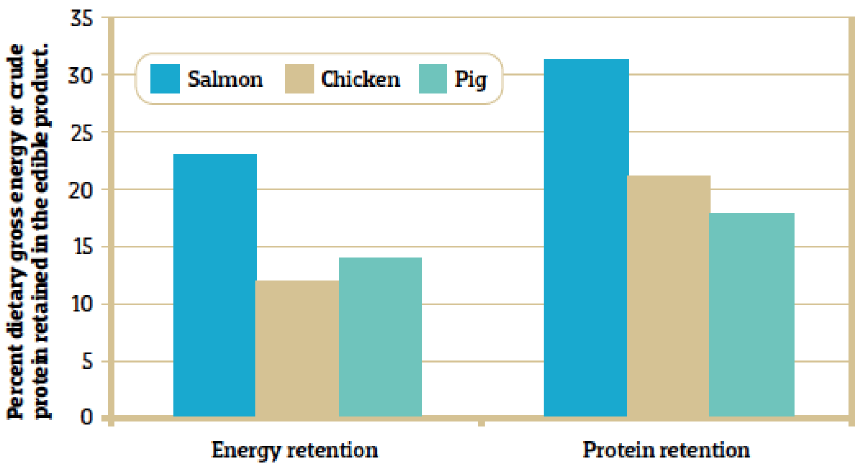


Fig. 4.1 Global Capture and Aquaculture Volumes (FAO 2012)

Aquaculture offers many opportunities for the provision of nutritious meat in a resource constrained-world. Driven by surging global demand for fish and stagnating yields of edible species from overexploited wild fisheries, aquaculture has been compensating for this shortfall with one of the fastest growth rates of any agricultural sector(see Figure 4.1) (FAO 2012).



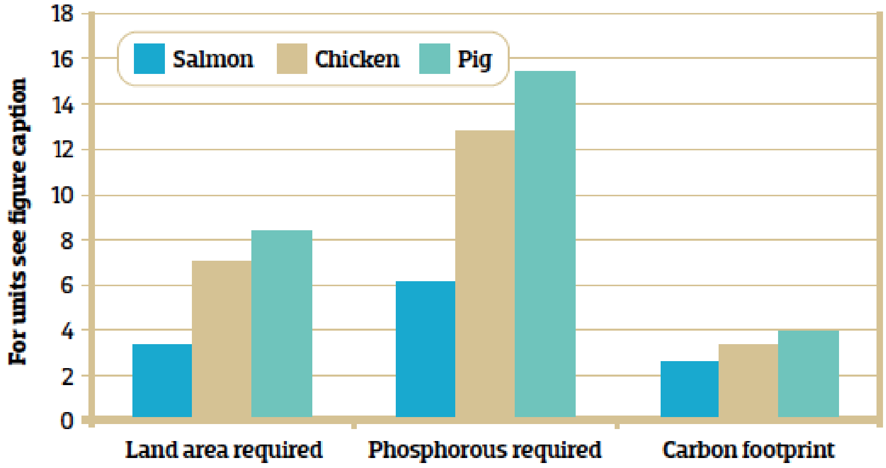


Fig 4.2 Comparison of Livestock Performance (Ytrestoyl et al 2011)

Aquaculture offers many opportunities for promoting food security in a sustainable way. Being water-based, its production does not compete with crops, at least in terms of rearing space. Modern aquaculture also happens to offer very efficient feed-to-body mass conversion rates, with species like salmon handily outperforming their closest terrestrial competitor, poultry (Fig 4.2). This benefit is even greater when considering the edible proportion of marine species when compared to terrestrial ones. High conversion rates ease price pressures on feed ingredients which could be used for human consumption. Lastly, aquacultured species offer a more complete nutritional profile and a better taste than many vegetable-based diets.

The Norwegian Aquaculture Sector

While only a tiny fraction of the scale of China's aquaculture sector, Norwegian aquaculture is the largest producer of farmed salmon in the world. Of the more than 1.2 millions tons of seafood grown in Norway, around 95% was Atlantic salmon (*Salmo salar*), with rainbow trout, and to a much lesser other species making up the rest. After fossil fuels, aquaculture products are the biggest export from the Norwegian economy at over 28 billion NOK per annum (Fiskeritdirektoratet 2012). It is also a growing industry, with a CAGR of 8% over the last 20 years despite stiff competition from low-cost production countries, such as Chile. In Norway, aquaculture employs around 6000 workers directly, with more supported indirectly by this activity (Fiskeritdirektoratet 2012).

Salmon is a cold-blooded predatory fish which starts its natural lifecycle in freshwater, before migrating to saltwater to grow and mature, then returning to freshwater to spawn. The majority of salmon consumed in the world is farmed, with the dominant species being Atlantic salmon (Marine Harvest 2012). Norway is geographically well suited for salmon production with its abundant fjords offering good hydrological attributes and shelter from extreme weather. A modern salmon production cycle takes place in distinct stages over the course of several years (Fig 4.3)

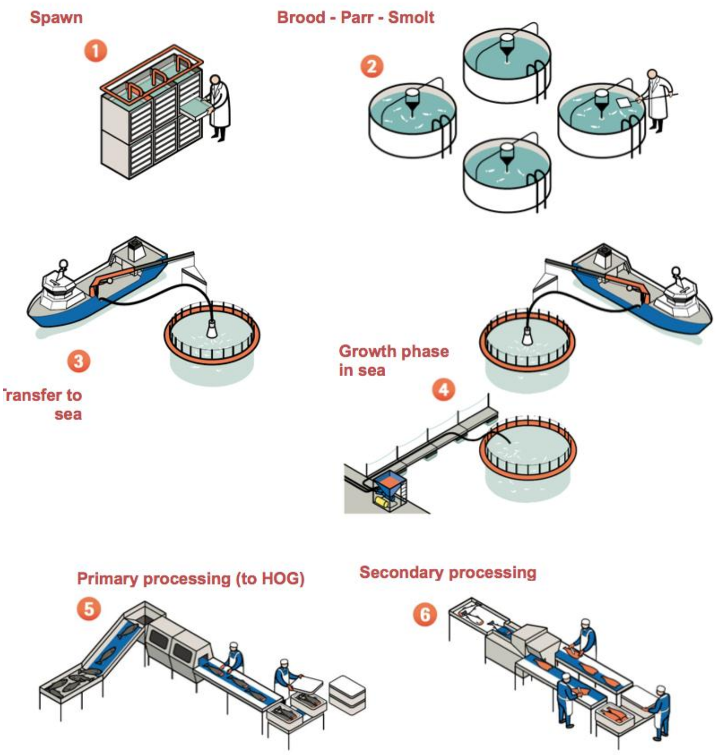


Fig 4.3 The production cycle of salmon (Marine Harvest 2012)

In this production cycle, a substantial majority of the economic value creation happens during the on-growing stage, where most of the biomass generation occurs. Though some small-scale salmon farms still use fairly traditional production methods, such as hand-feeding, the bulk of the on-growing activity in Norway is done in process-based operations using large diameter cages containing many tons of fish. Fish are fed dry pellets by machines, sometimes entirely automatically, while their intake is monitored remotely by cameras or other sensors. Often, only small crews are required to tend to many pens. A single worker may manage millions of NOK of fish at a time, making labor costs a comparatively minor expense. These technologies have reduced proportional costs for many production inputs, but to a lesser extent feed (Fig 4.4). Therefore, like other modern animal husbandry operations, feed can make up to 60% of production costs.

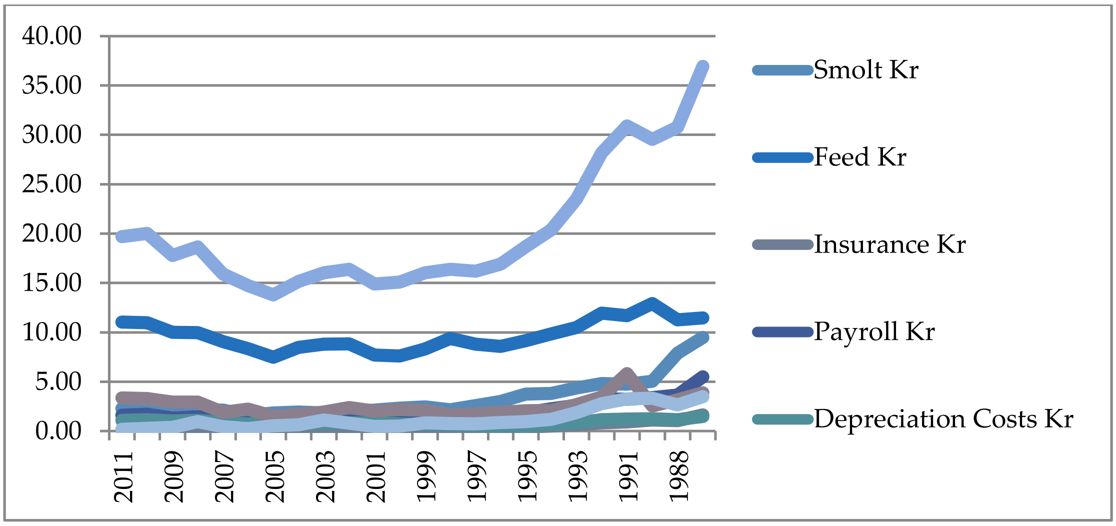


Fig 4.4 Average salmon production costs in Norway, NoK/Kilo (Fiskeritdirektoratet 2012)

While Norwegian salmon production began as a fragmented industry populated by small-scale producers around 30 years ago, it has consolidated considerably in the last two decades as a result of technological innovation, economic forces and policy shifts (Fig 4.5). Furthermore, it has also seen a degree of vertical integration that is relatively rare in other agriculture industries, as salmon producers have acquired upstream breeding facilities and downstream processing plants (Aslesen 2009).

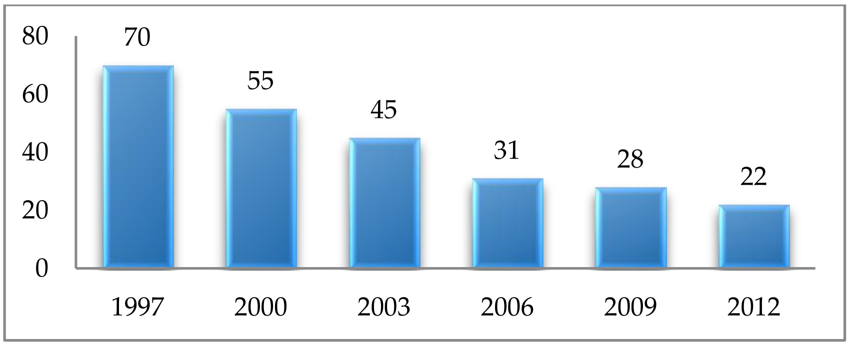


Fig 4.5 Number of firms producing 80% of salmon in Norway (Marine Harvest 2012)

Besides salmon production, the Norwegian sector is also a world leader in aquaculture innovation, although relatively little of this is attributable to salmon producers themselves. Instead, most new technologies are introduced by suppliers, a result of collaboration with research institutes and universities (Aslesen 2009). Overall, the Norwegian government has played a key role in building the network of institutions that has been critical to knowledge generation in the industry. Ever since several fish health crisis threatened the growth of the industry at the end of the 1980s, the government has taken an active approach in knowledge development through programs, such as Frisk Fisk and Havbruk, that reinforce the technological and scientific competencies of the industry. The results of these efforts are reflected in Norwegian publications on fisheries and aquaculture research, which were the most cited in the world, even if they only constituted 4.2% of the total volume of research on the topic. (NIFU 2012)

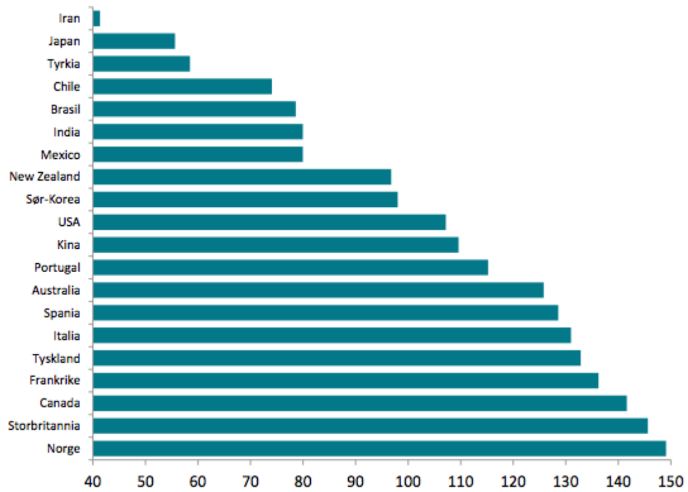


Fig 4.6 R&D Investments in Fisheries and Aquaculture R&D (100=global average) (NIFU 2012)

The marine aquaculture sector in Norway is also strictly regulated and tightly monitored (Maroni 2000). In collaboration with the Ministry of Fisheries, authorities from various branches of the government enforce a wide range of policies concerning environmental impacts, labor, and consumer health through licensing and regulation. These measures align with food safety and other regulations in its largest export market, the EU. Norway serves as the host country for the Codex Alimentarius Commission's Committee on Fish and Fishery Products, which develops international standards to facilitate trade and protect the health of consumers.

Besides mandatory measures, many members within the Norwegian sector have been involved in voluntary certification and ecolabeling schemes, such as those of the Marine Stewardship Council, World Wildlife Fund for Nature (WWF) salmon aquaculture dialogue or that of the International Fishmeal and Fish Oil Organization (IFFO) (Sorensen, et al. 2011). These schemes are especially important for marketing purposes in the EU where some large retailers, such as the German chain Metro, have adopted sustainable sourcing requirements.

A Fishmeal Trap?

Fishmeal and fish oil (FMFO) have a long history as feed ingredients in Norwegian aquaculture. Considered as the "Gold Standard" in carnivorous fish nutrition (Sorensen, et al. 2011), both are primarily produced from small pelagic fish, such as anchoveta, harvested in large quantities from wild "forage" fisheries, , although in recent years FMFO have increasingly been derived from by-catch and fish offal.

Fishmeal is a powder containing 51-74% protein, depending on the species it is derived from and the way it was produced (ibid). Fish oil is a liquid usually extracted in the same process and is unique in that it contains very long chain fatty acids, such as omega-3 and -6, which are not present in other raw materials. It is also worth noting that varying fat content in forage fish often lead to fluctuations in the world supply of fish oil.

While originally cheap and plentiful, the supply of FMFO has been of great concern to the Norwegian aquaculture industry for at least the last 20 years. Because of a lack of easy substitutability with other protein sources, the concept *fishmeal trap* was used to describe the threat facing many aquaculture industries whose production regimes were based on the availability of these ingredients.

During the 1990s, trends suggested the *fishmeal trap* could actually materialize and devastate the industry. In contrast to growing aquaculture production, world FMFO production began to plateau as a result of fishing quotas and other environmental factors (Fig 4.7). For a while, this did not constitute a problem as the aquaculture firms were willing to pay a premium for FMFO, thus diverting their use from other less dependent industries. However, as aquaculture began to consume the majority of world production, there was little room for further diversion and FMFO prices began to rise considerably, driven by demand within this industry. This put substantial pressure on the long-term economic viability of the industry.

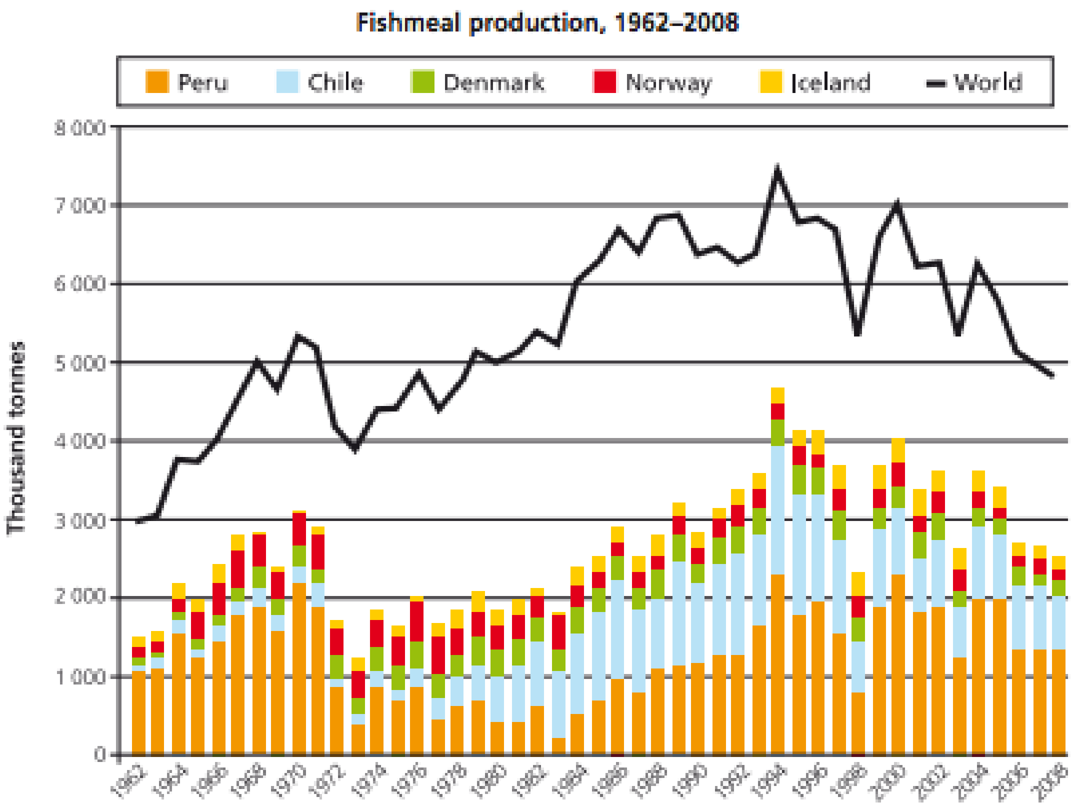


Fig 4.7 Global Production Volumes of Fishmeal (Shepherd 2009)

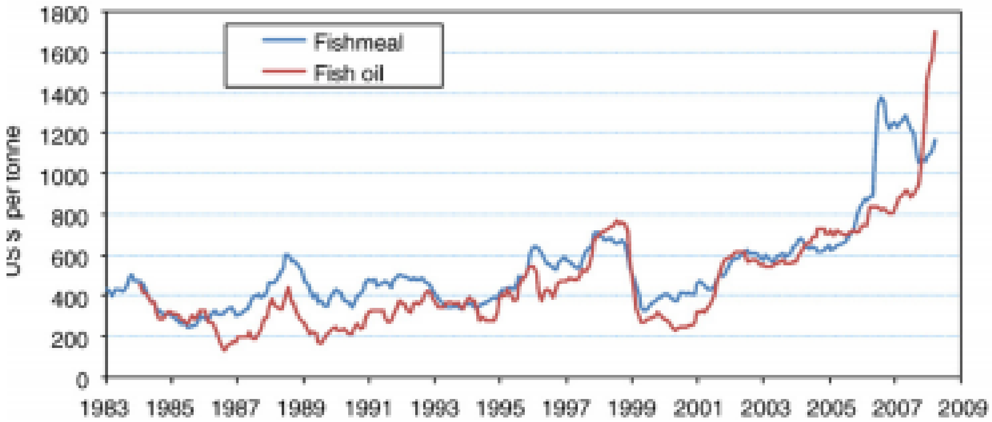


Fig 4.8 Historical development of FMFO prices (Tacon et Metian 2008)

Aside from the economic implications of FMFO use in aquaculture, questions have abounded about its social and environmental impacts. These arguments revolve around the Fish-In-Fish-Out (FIFO) ratio of production regimes using these ingredients, which can be seen as inefficient. It has been argued that aquaculture growth drives large-scale harvest of forage fish, putting unnecessary pressure on marine ecosystems. Also, criticism abounds on the claim that reduction fisheries divert small fish away from consumption by humans in poorer countries. These issues have been addressed in research and there is no consensus that FMFO use in Norwegian aquaculture leads to the decline of human consumption of fish in developing countries or to systematic overfishing (Huntington et Hasan 2009). This is especially true because Norwegian FMFO is sourced from well-managed fisheries in the North Atlantic and South East Pacific. That said, the use of marine ingredients in aquaculture in countries such as China and Vietnam has been linked to unsustainable fishing practices.

5. Two Waves of Innovation

This section describes technological innovations that have reduced FIFO rates in Norwegian aquaculture production.

Innovation and FIFO Rates

Regardless of the reasons driving it, the Norwegian salmon industry has made major progress over the last 30 years in lowering its FIFO ratio, while growing and remaining profitable. This success can be ascribed to two waves of innovation that have swept through this sectoral system.

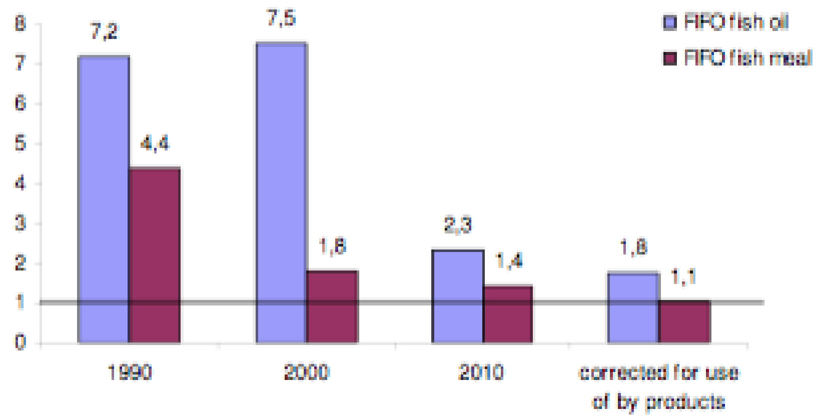


Fig 5.1 Historical development of FIFO ratios for Norwegian salmon farming (Ytrestoyl et al 2011)

The first wave of innovation reduced the feed intensity of Norwegian salmon production, or Feed Conversion Ratio (FCR), through a shift in production regimes in the 1980s and early 1990s (Asche, Roll et Tveteras 2009). During that time, the sector transformed from a traditional industry into the modern process-driven sector it is today as a result of the introduction of many efficiency-driving technologies.

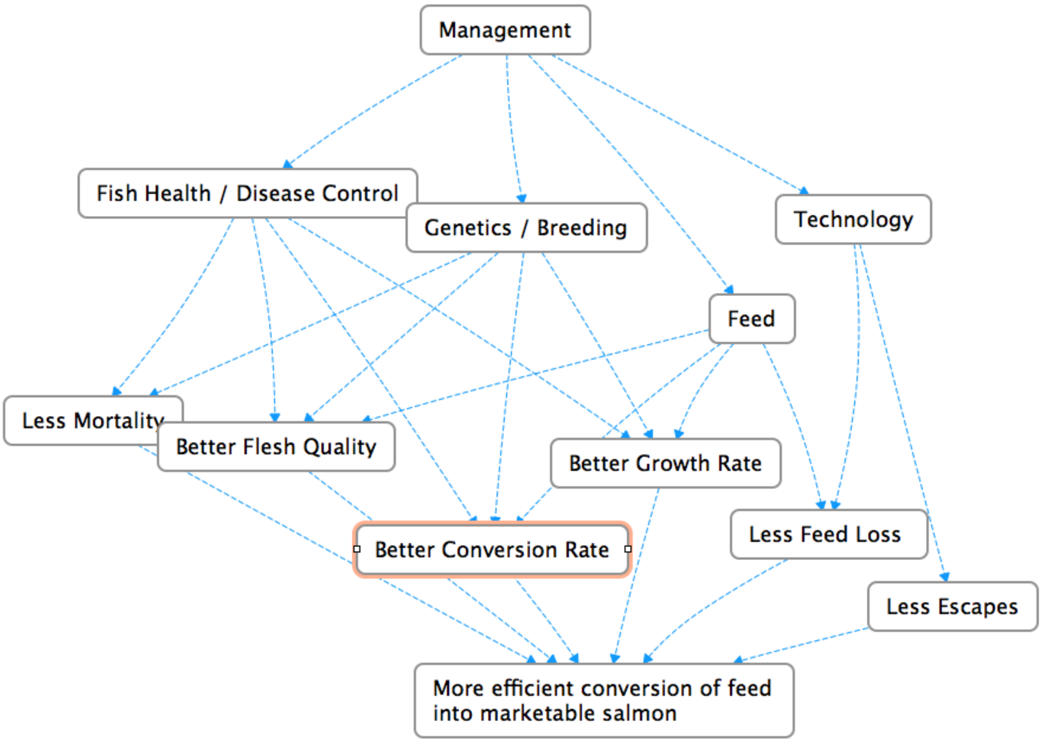


Fig 5.2 Innovations in salmon aquaculture technology from the "First Wave"

First of all, advances in fish health and disease control, such as medication and vaccination, helped prevent epidemics in captive salmon populations. This improved health, growth rates, and feed conversion rates while reducing mortality rates. Concurrently, innovations in feed contributed to better biological conversion rates in the form of nutrient efficiency, and to some extent, better fish health. Improvements in feed also related to pellet quality, making them less likely to be degraded and wasted during feeding. Genetics and breeding created strains of fish that were more resistant to disease, better at converting feeds into edible body mass, and generally faster growing, requiring lesser quantities over their lifecycle. Technology, which in this industry is defined as production machinery, such as cages and feeding systems, improved process control. Advanced feeding systems could help deliver feed more efficiently and reduce the amount of wastage.

Finally, better management practices played a role in the implementation of these technologies and the optimization of resource allocation. All of these innovations synergistically contributed to better feed efficiency, which in turn reduced the amount of FMFO required to produce a kilo of salmon (Asche, Roll et Tveteras 2009)

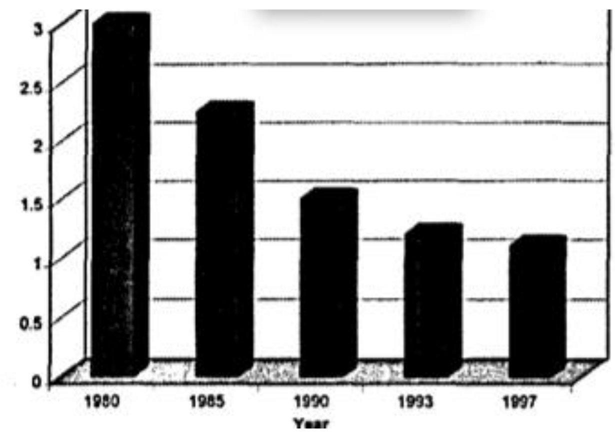


Fig 5.3 Average Feed Conversion Rates for Salmon in Norway (Asche et al, 1999)

As a result of these innovations, between 1980 and 1995, the average FCR of the Norwegian sector dropped from around 2.8 before leveling off at about 1.2, about their current level. This trend towards feed efficiency is a common occurrence in other animal husbandry industries, like poultry. At the time, this FCR was excellent and even today remains below world averages (Tacon et Metian 2008). Since 1995, many of the innovations developed and adopted by the industry have focused scaling up cage sizes. The relationship between cage diameters and the biomass they contain is exponential; larger cages decrease process control substantially with effects on economic FCRs. To remain competitive, many innovations in the last 15 years have focused on solving scale- related production control problems.

The second wave of innovation regarding FIFO rates, the emergence of Dynamic Formulation feed technology, began in the late 1990s. Feed was already being used to the limits of efficiency, so any further reductions in overall marine ingredient usage had to come from their substitution. Unlike the previous wave of innovation, where many innovations from different suppliers in the sectoral system combined to collectively reduce FIFO rates, this one was primarily driven by just one cluster, the feed sub-sector.

The Second Wave

The "Second Wave" of innovation marked a dramatic decrease in the overall inclusion rates FMFO in salmon feed seen in Fig 5.3. This data must be interpreted with a grain of salt, however, because inclusion rates do not have a linear relationship to the technological advances implicated in this change. FMFO can be crudely substituted in salmon feed up to a certain point, after which performance begins to suffer. So, while the absolute change in fishmeal inclusion between 1990 and 2000 was greater than that between 2000 and 2010, it was mainly economics that drove this change in the former and technological progress in the later.

	1990	2000	2010
Fish meal	63.8	37.5	25.6
Plant protein (various sources)	0	15.4	36.9
Starch (mainly wheat)	10.3	10.9	9.4
Fish oil	23.4	30.7	17.0
Plant oil	0	0.0	12.0

*Microingredients such as vitamins, minerals and amino acids are excluded

Fig 5.3 Average compositions of Norwegian salmon feed (Sorensen, et al. 2011)

For lack of a better alternative, the term *Dynamic Formulation* (DF) was coined to represent the technology central to this second wave. DF covers the range of applied knowledge used in the production of aquafeeds whose composition can shift without negatively impacting the performance of the production systems in which they are used. Following trends in FMFO scarcity, development of this technology has centered on the substitution of these ingredients with mostly plant-based ones, although even these may be replaced by other, yet unknown, ingredients in the future. DF technology is reliant on scientific knowledge and technological progress in three related but separate fields (Fig 5.4).

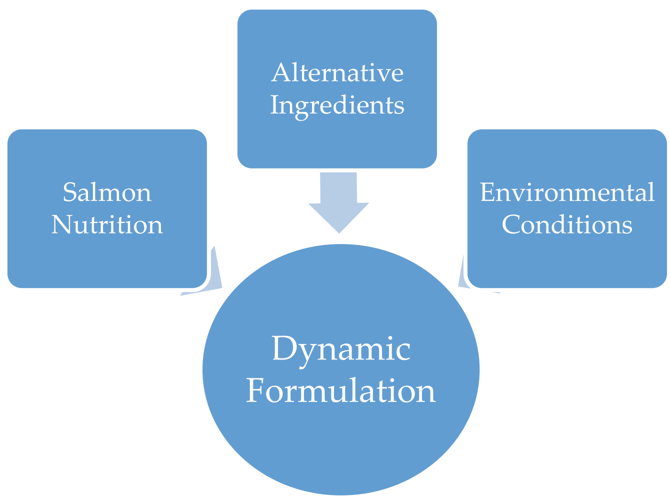


Fig 5.4 Dynamic Formulation

Dynamic Formulation

During the first wave of innovation, feed technology in Norway progressed from crude FMFO pellets to energy-rich, dry, extruded pellets. (Fig 5.5) In the 20 years since then, extruded feeds have been the dominant design and form the platform of DF technology. While DF feeds may look similar to traditional feeds, their difference lies in their composition.

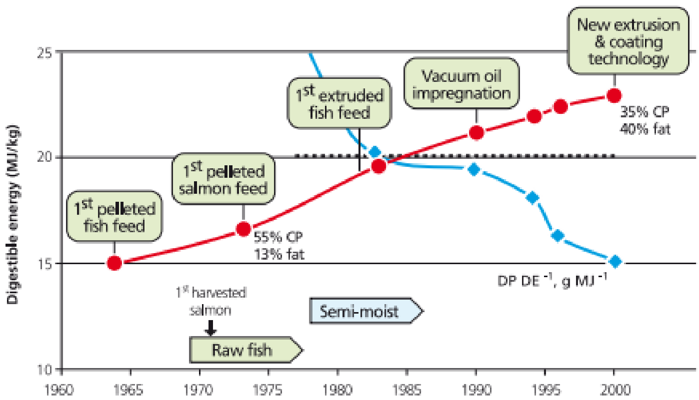


Fig 5.5 Technological evolution of Norwegian salmon feeds (Talbot 2002)

Fig 5.6 Modern extruded salmon feed

Dynamic Formulation, as a commercial technology, needs to satisfy biological requirements of fish as well as economic needs of farmers. Since DF feeds replace FMFO, they require a wider range of inputs than were previously used and can easily contain ten or more ingredients (Fig 5.7). The supplies, prices, and nutritional content of these ingredients vary. To match these changing conditions, feed formulations must be able to float accordingly while retaining process performance. Hence, DF technology is not so much about creating the "ideal" feed composition as it is about "flexibility", or the ability to dynamically optimize feeds in the face fluctuating market conditions. So, while it has been possible, for some time already, to create high-performing feeds with little or no FMFO content in laboratory conditions, these feeds do not truly embody DF technology, as they are effectively expensive "prototypes". Described in this way, the heart of DF technology resides in the tools, organizational processes, and tacit knowledge implicated in the complex balancing of ingredients.

Function	Typical Ingredients
Energy	Fish Oil, Soybean Oil, Rapeseed Oil
Protein	Fish Meal, Soy Protein Concentrate, Sunflower Meal, Lupine Meal, Pea Protein Concentrate
Micro Nutrition	Fishmeal, Mineral Additives, Vitamins
Binder	Wheat Starch

Fig 5.7 Examples of ingredients in Norwegian salmon feed (Sorensen, et al. 2011)

Yet DF technology also takes into account the manufacturing process of these feeds (Fig 5.8). The extrusion process used to create them is complex and affects the physical attributes of feed such as buoyancy. Alternative ingredients cause variance in this process and DF technology includes the knowledge specific to solving these issues. For instance, in feeds where fish oil had been replaced with rapeseed oil, seepage was an issue because of the lower viscosity of the latter. This was corrected by implementing a coating process that effectively sealed the oil inside of the pellet.

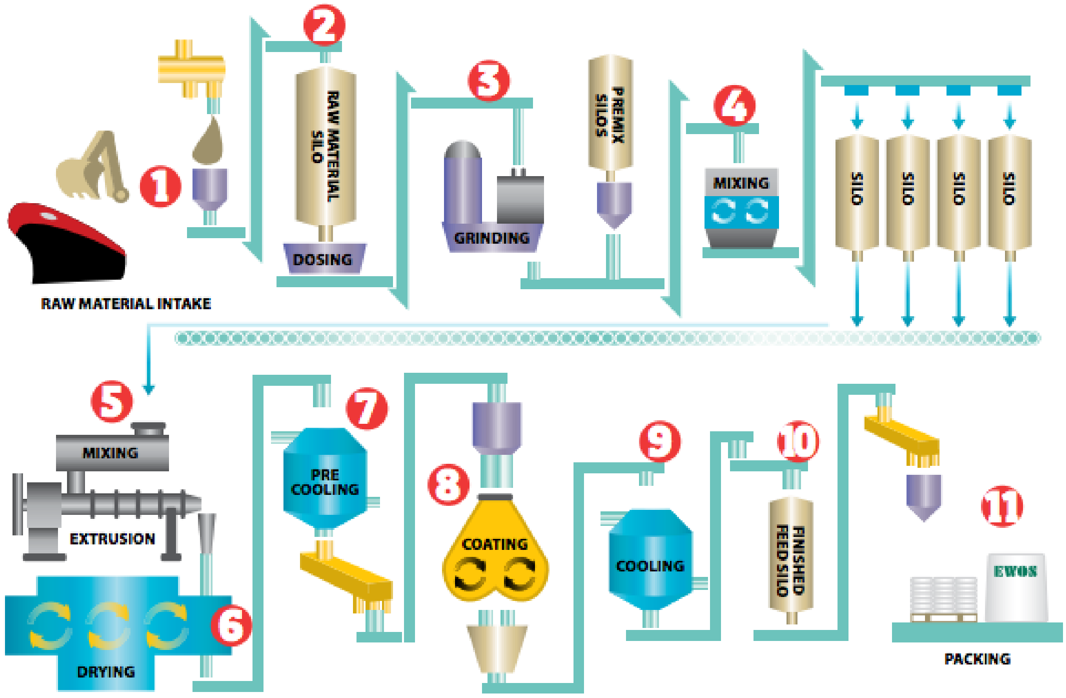


Fig 5.8 Feed Production Process (Ewos 2011)

Salmon Nutrition

While certain physiological traits may have been tempered by domestication efforts, salmon, like humans and housecats, still exhibit evolutionary path-dependency and remain biologically optimized for a diet of marine animals that provided a highly digestible "package" of lipids, amino acids, and micronutrients. Generally, feeds with high levels of FMFO promote fish health, welfare, and growth. Replacement of FMFO in feeds entails at least some degree of underperformance because of a deviance of the attributes of the feed from its marine “ideal”. From a biological perspective, a main knowledge prerequisite for resolving this gap lies in the science of salmon nutrition, which relates both to their metabolic needs and to their physiological responses to different ingredients.

Nutritional Requirements

Determining the exact nutritional inputs required to promote optimal production performance requires an understanding of underlying biological systems of salmon. With knowledge of the functions and interactions of these systems, progress can be made towards more precise estimates of the quantities and proportions of nutrients needed. These can then serve as guidelines for the creation of feeds bypassing these nutritional “bottlenecks”.

The best example of how this science has been applied in dynamic formulations relates to salmon amino acid requirements. Based on findings that certain proportions of amino acids encouraged better FCRs, feed producers could correct the nutritional profiles of soy-based salmon feeds to compensate for deficiencies in limiting nutrients like methionine.

Another example would be the identification of selenium as a key micronutrient. Although present in minute quantities in fishmeal, its relative absence in early plant-based DF feeds was linked to higher instances of cataracts in farmed salmon.

Of special importance right now is the issue of omega-3 fatty acids retention. Farmed salmon are not net producers of omega-3 fatty acids, instead absorbing it from the fish oil in their diet. As fish oil has been gradually been replaced with plant oils poor in these long-chained fatty acids, much research has been focused on understanding the relationship between their intake of omega-3 fatty acids in feed and its presence in the final product. Advances in metabolic studies allowed for feed producers to set an inclusion rate leading to an efficient utilization of these expensive and scarce oils while maintaining a level of omega-3 fatty acids acceptable to consumers.

Ingredient Interactions

Raw materials consist of countless compounds, in quantities varying from grams to micrograms. Some of the compounds may be difficult for salmon to digest and metabolize, even if they can, in principle, perform certain nutritional functions. Others may have negative, even toxic effects when ingested by salmon. Therefore, it is as important to understand both the exact nutritional makeup of ingredients and their interactions with the salmon physiology.

Taking the example of plant-based ingredients again, crude soy meal had high levels of a compound causing enteritis, inflammation of the digestive system, as well as anti-nutritional components. Identifying these compounds as the culprits of poor feed performance allowed for the development and utilization of advanced soy-based preparations from which these elements had been removed. This type of innovation has contributed to further use of rapeseed, sunflower, and other protein meals as well.

A third issue, of slightly lesser importance, is that of salmon feeding behavior. Many non-marine ingredients lack the appeal that FMFO has to salmon, meaning that they are less inclined to eat them. By understanding feeding behavior, DF feeds can be designed to be more appetizing to salmon, reducing their tendency to be wasted and stimulating feed intake to optimal levels.

Huge progress has been made in these fields, yet interviewees freely admitted that there is still much to be understood about salmon and their needs. Salmon nutrition is based on contributions from many fields of science, with each study or project revealing only a small glimpse of the inner workings of these fish.

Alternative Ingredients

The attractiveness of DF technology lies in its ability to integrate a variety of different ingredients into high-performance feeds. But, as was said previously, not all ingredients are suitable for this application. So, the development of DF feed technology must be accompanied by a similar push to expand the range of ingredients available to feed producers though the identification of new raw materials with attractive nutritional and digestibility traits. Furthermore, to be viable alternatives, these ingredients must be produced economically, sustainably, and in suitable quantities for feed producers. Over the years, raw materials from a wide variety of different sources have been investigated, some very conventional and others less so (See Fig 5.9).

Commodities already used in other livestock production, like plant protein meals, have been the subject of development efforts intended to reinforce their nutritional value in salmon feeds through improved processing techniques. As mentioned earlier, it was advances in processing that led to the widespread use of soy in feeds. Genetics and breeding are also used to adapt chemical profiles of plant ingredients to aquaculture-specific needs. The main draw of these raw materials to the feed industry is that they can be economically produced in large quantities through established supply chains. It must be noted that because of EU regulations, Norwegian feed producers have not been able to include ingredients made from animal by-products and GMOs, despite their qualities in salmon nutrition. These ingredients are, however, commonly used in Chile and Canada.

Unconventional ingredients, such as insects and bacterial meals, can sometimes exhibit attractive nutritional and sustainability attributes yet lack the technology to be produced at the scale and cost needed by the feed industry. This "exotic" ingredient research isn't necessarily conducted with the application of salmon feeds as its main priority but rather with the generic goal of developing new sources of protein. DF feed-specific research occurs when sources are further developed to match the requirements of aquafeeds. Some of these ingredients are especially promising from a food security perspective because they are derived from sources that do not compete with the production of food for humans, like slaughterhouse byproducts.

Ingredient	Characteristics
Krill	+Delicious (to salmon) and nutritious -Expensive to produce -Effects of harvest still unclear
Microbial Preparations	+Highly nutritious -Highly expensive
Genetically Modified Plants	+Possible high-volume source of omega-3 fatty acids -Negative public perception -Environmental effects still unclear

Insect Meal	+Recycles nutrients from waste +Good nutritional profile -Lack of large-scale production technology
Blue Mussel	+Captures and reuses waste from salmon production -Unresolved issues regarding food safety

Fig 5.9 Unconventional alternative ingredients (Sorensen, et al. 2011)

The provision of omega-3 fatty acids is a major driver in new ingredient development because its only current source is fish oil. In the face of fish oil scarcity, the race for other natural sources is on. Promising sources of economically viable omega-3 are microalgae, yeast, and genetically modified plant crops, although interviewees viewed them as more medium-to-long term solutions because of the need for further development. This issue has acquired a degree of urgency for the salmon industry in the face of mounting competition from dietary supplement production from the same fish oil supplies. It is worth noting that from a FIFO perspective, salmon is a superior omega-3 fatty acid vector for human consumption because of inefficient industrial separation techniques used in supplement production. (Ytrestoyl et al 2011)

Functional ingredients, which are added in minute amounts to perform certain roles, such as micronutrients, are also increasingly a subject of research. The role of these ingredients in balancing the nutritional profiles of feeds is becoming pivotal as fishmeal inclusion rates decrease to unprecedented levels. While some of these functional ingredients are industrially produced compounds like crystalline amino acids and vitamins, others that have been explored are biological in nature, such as krill. These ingredients are especially important in the formulation of functional feeds, which target specific aspects of production performance, such as disease, parasite, or stress resistance.

Environmental Conditions

Complicating the development of DF feeds is the range of environmental conditions at the production sites in which they will be used. Environmental factors like temperature, water salinity, daylight, and water quality vary tremendously between farms in Norway's polar regions and those thousands of kilometers south. Production technology, methods, and objectives also vary between producers and locations. These factors influence production system requirements, biological processes, and feed performance. Certain fats, for example, solidify at cold temperatures and create problems when used in operations above the polar circle. The cumulative effect of these factors can render certain feeds unusable in different conditions. There is a continuous R&D effort to better adapt feeds to site-specific needs and integrate them with supply-chain technology.

Complementary Technologies

Besides First Wave innovations and the emergence of DF feeds, other technology is helping to improve the FIFO ratio for Norwegian salmon. The practice of managing the types, quantity and timing of the delivery of the feeds to salmon, which is called a "feeding regime" can be used to optimize the use of marine resources. One feeding regime is to increase the use of feed rich in fish oils, which are not strictly necessary for fish health but contributes to high omega-3 levels in salmon flesh, right before slaughter. This produces fish with similar levels of omega-3 to those that were fed diets rich in fish oil over their whole life cycle. Based on this concept, feed producers, and even some of the larger salmon producers have developed dynamic models used to inform feeding regime implementation.

New technology to process by-catch and trimmings from edible fish could increase the supply of fishmeal and oil without corresponding increases in marine harvesting. Finally, advances in salmon genetics could one day lead to the creation of fish capable of synthesizing healthy fatty acids in their own bodies, instead of simply extracting them. Though the technology is far from viable, it has the potential to make salmon a net producer of omega-3. The author could envision collaboration between feed suppliers and breeders to develop feeds with the metabolic precursors of omega-3.

Conclusions on DF Technology and Industry Viability

After reviewing available literature on the topic, it would appear that DF technology is overall a sustainable technology because of its ability to reduce FMFO intensity in feeds. Marine ecosystem dynamics are poorly understood, especially with regards to global warming and ocean acidification. Because of "shifting baselines" (Pauly 1995), maximum sustainable yields may be overestimated in many fisheries. The highly interconnected nature of global resource consumption patterns which perpetuate secondary effects is an important feature. Therefore, this author advocates a precautionary perspective to FMFO utilization, the less of it consumed, the better.

Concerns have been raised about the sustainability of plant-based ingredients that replace FMFO based on their production and transportation impacts.

These are legitimate concerns but, like many other environmental impacts, are hard to measure and analyze. These ingredients are sourced from countless different suppliers in numerous geographic locations. However, DF technology opens possibilities for the use of many other ingredients in the future, which could be almost objectively described as sustainable.

From an economic viability perspective, DF technology can be seen as a savior to the industry. FMFO prices have only increased over the last decade but feed prices, in large part because of DF, have remained comparatively stable. For an industry as sensitive as Norway's is to feed costs, this technology has brought with it resource security that has allowed further growth and development.

6. The Norwegian Aquafeed SSPI

This section describes the characteristics of the Norwegian Aquafeed sector using the Sectoral System of Production and Innovation (SSPI)approach.

The Aquafeed SSPI

Of the suppliers to the Norwegian aquaculture industry, the aquafeed subsector is the largest and is developed enough to be labeled as a SSPI unto itself, the Norwegian Aquaculture Sectoral System (NASS). This SSPI specializes in the development, production, and distribution of dry extruded feeds for farmed aquaculture species in Norway, the great bulk of which is salmon. Nearly all of this is produced domestically (Fig 6.1). Besides aquafeed for a wide range of production conditions and requirements, the feed producers sell intangible products such as consulting services and feed-management programs, to salmon producers to optimize process performance. Knowledge and research services can also be considered a product of this SSPI, since they are often used to create value outside of Norway.

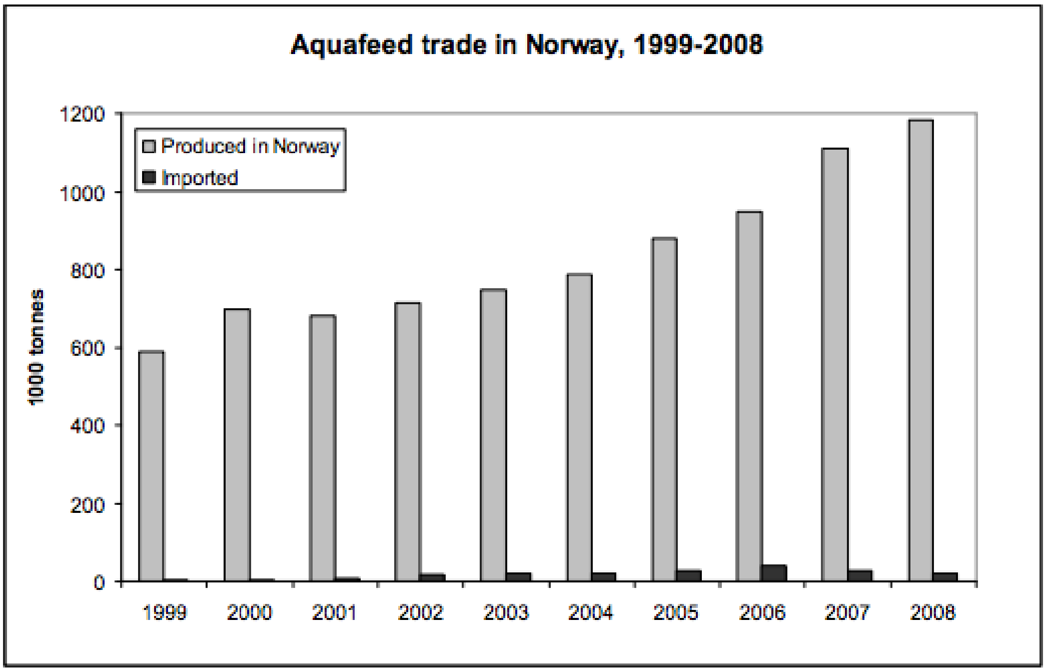


Fig 6.1 Aquafeed trade in Norway

Feed Firms

Central to the SSPI are the feed firms themselves, who together constitute a profitable oligopoly (Fig 6.2). The strong growth of the feed subsector has followed that of the salmon industry. Outside of Norway, these companies also happen to be the largest commercial aquafeed producers in the world. Although a large proportion of their income comes from the Norwegian salmon sector (6.3), in recent years, these companies have sought to expand into Asian and South American markets and now produce feeds for over 60 species.

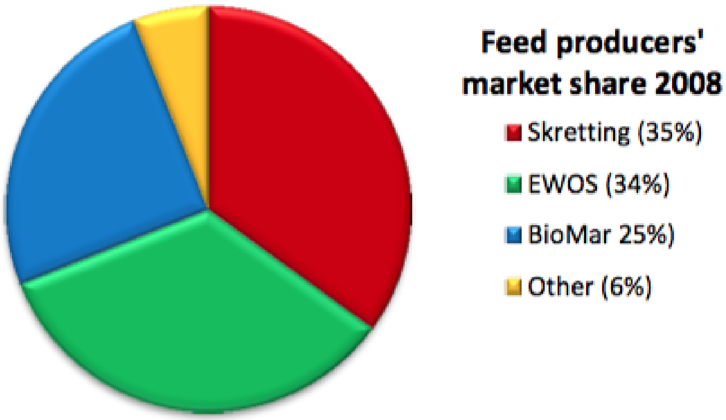


Fig 6.2 Shares of global salmon feed production (Marine Harvest 2012)

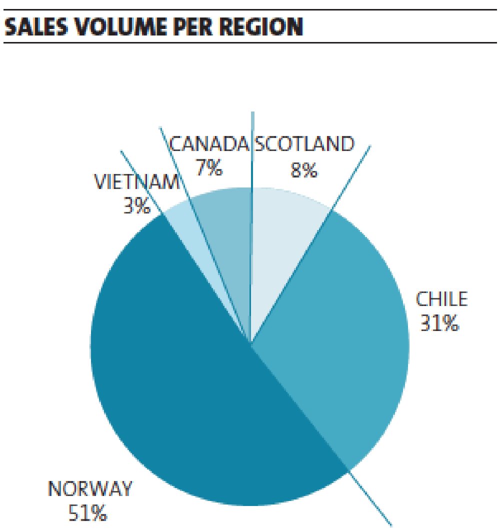


Fig 6.3 Sales volumes per region (Cermaq 2012)

Skretting, traditionally the largest of the three firms, has been a strong innovator and encompasses all the aquafeed operations of its parent company, the Dutch animal feed giant Nutreco. It has long benefited from linkages with research conducted in other business units. While Skretting has production and research facilities around the world, its own R&D network is centered on the Aquaculture Research Center (ARC) in Norway, which includes a pilot feed production plant, a feed trial station and an analytical laboratory.

EBITA margin per segment	
Premix & Feed Specialties	6.7%
Animal Nutrition Canada	4.4%
Compound Feed	3.3%
Meat & Other	2.4%
Fish Feed	7.5%
Nutreco total (continuing operations)	5.0%

Fig 6.4 EBITA of various divisions at Nutreco (Nutreco 2012)

The result of the consolidation of smaller feed producers in the 1990s, Ewos is a subsidiary of Cermaq, the 4th largest salmon producer in Norway. It is headquartered in Bergen and has two research facilities under its Ewos Innovation division in Norway and a third in Chile. Ewos has the advantage of being closely integrated with salmon production, which aids collaboration efforts.

Owned by the Danish conglomerate Schouwe, Biomar is the smallest firm of the three and was described as being slightly less focused on DF technology because of an emphasis on health-promoting functional feeds.

While this case was being written, Marine Harvest the largest salmon producer in the Norway, made an attempted hostile takeover of Cermaq, the parent company of Ewos. This came after the company had already made waves by initiating the construction of its own 220,000 ton feed plant in December. The results of this entry are not yet clear and many interviewees were somewhat surprised by it.

Aquaculture Producers

Within the NASS, salmon producers are value-sensitive and demanding customers. “Salmon producers often buy feed from two different companies,” said a member of the feed industry, “They’ll buy from whichever one offers the lowest price at a given time.” Many salmon producers sign floating contracts that allow for formulations to vary in the face of commodity price fluctuations.

But price is not all that counts, as feed performance is extremely important to process control and profitability. Salmon producers will often demand high levels of documentation on the performance of feeds in tests. Also, since feed attributes affect the final product, salmon producers serve as a proxy for the demands of markets and their governing institutions. Sustainable ingredient sourcing, nutritional content, and meat quality are examples of these “transmitted” performance demands. Sustainability issues, especially, are gaining importance for larger producers where corporate reputation is a concern.

Materials Suppliers

Salmon feed is produced from agricultural commodities, FMFO, and functional ingredients. Interactions between feed producers and their suppliers vary, with some being limited to simple transactions and others being R&D and sustainable sourcing partnerships. The commodity suppliers have been described as being rather distant because of their lack of strategic involvement in aquafeeds. Ingredient processors have been described as having a slightly larger role in customizing commodities to meet certain parameters. Functional ingredients, on the other hand, are sourced from more specialized suppliers, some of which are highly dependent on the aquaculture industry and have been more engaged in aquafeed technology.

Research Institutions and Universities

The NASS benefits from a national knowledge network of over 15 research institutions and 10 universities with competencies in aquaculture. With regards to feed technology, Akvaforsk, NOFIMA, SINTEF and UMB are just a few of the actors active in the field. These institutes conduct world-leading research and possess specialized competencies and facilities. These resources have been useful to the feed industry, particularly when addressing certain technological bottlenecks. Furthermore, the Norwegian knowledge network is well connected internally and internationally, enabling the transfer of the latest ideas.

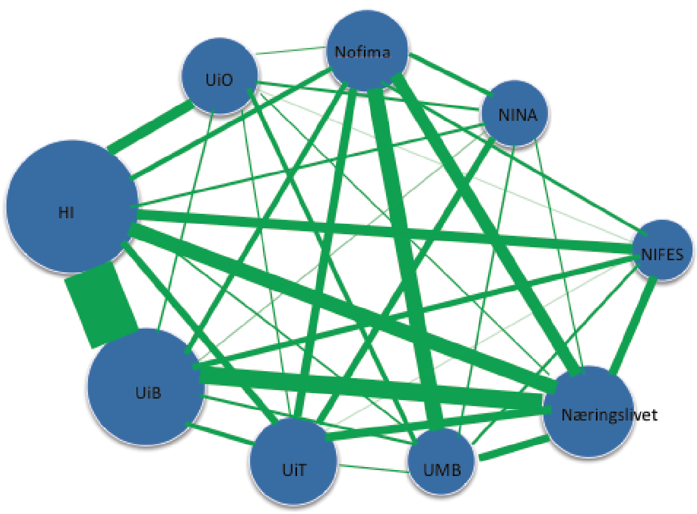


Fig 6.5 Collaboration between industry, universities, and research institutions on aquaculture and fisheries projects (NIFU 2012)

Universities also play an important role in providing the human resources necessary to undertake aquaculture research. A series of reforms in 1994 aimed to make the universities suppliers of human capital to reinforce the competitiveness of Norway's aquaculture and fisheries industry (Aslesen 2009).

Technology, Inputs, and Competition

The technological base of the NASS relates to the logistics, formulation, manufacture, and use of feeds in commercial operations. Since broad knowledge bases are a pre-requisite for producing the large quantities of high-performance feed demanded by customers, the industry can be seen as knowledge intensive and driven by technological competition. Today, aquafeed production in the NASS is dominated by two technologies: DF technology and functional feed technology. While DF feeds tend to focus on economic FCRs, functional feeds emphasize specific performance benefits, such as fish health or lice control and are generally more expensive. These feeds include higher levels of expensive ingredients like FMFO or additives but are gaining market share. Together, both technologies are used either symbiotically or discretely in nearly all the aquafeed sold in Norway.

Dynamic Formulation Technology

- Economic FCR
- Biological FCR
- Cost
- All-round acceptable performance
- Acceptable meat attributes

Functional Feed Technology

- Stress Resistance
- High Growth Rate
- Lifecycle-specific needs
- Fish health
- Parasite resistance

Fig 6.6 Technology performance characteristics

In standard feeds, over 80% of feed production costs come from raw materials, so advances that lead to even small reductions in expensive ingredients can translate into substantial cost savings. This is especially important during price spikes (Fig 6.7), where the differences between ingredient prices may increase exponentially. As a result, the competitive focus of the industry over the last 15 years has centered on DF technology.

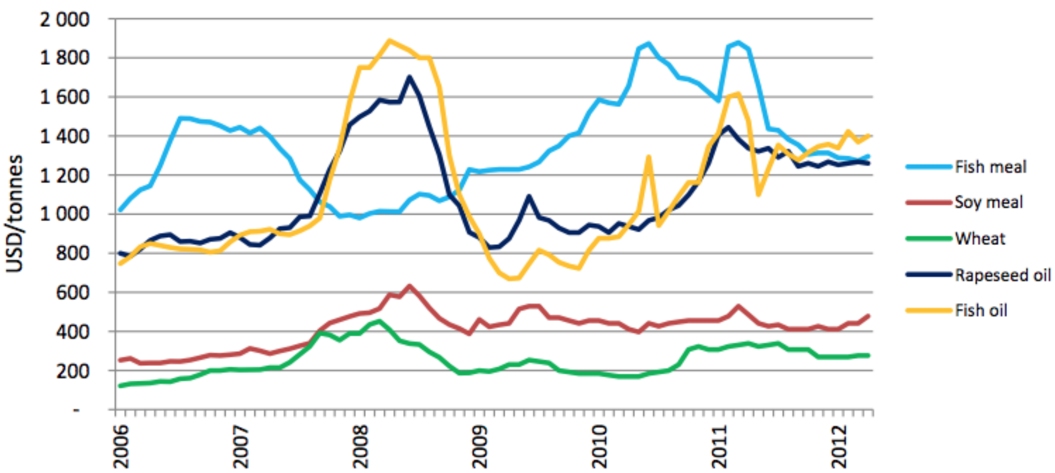


Fig 6.7 Commodity prices (Marine Harvest 2012)

In contrast to many of their customers, the feed companies are best described as a hybrid between Scale and Science-based firms in Pavitt's typologies. Their competitive positions are directly linked to their innovation strategies, and justify large expenditures. These investments can be distributed over the large revenues of the feed companies (Fig 6.5).

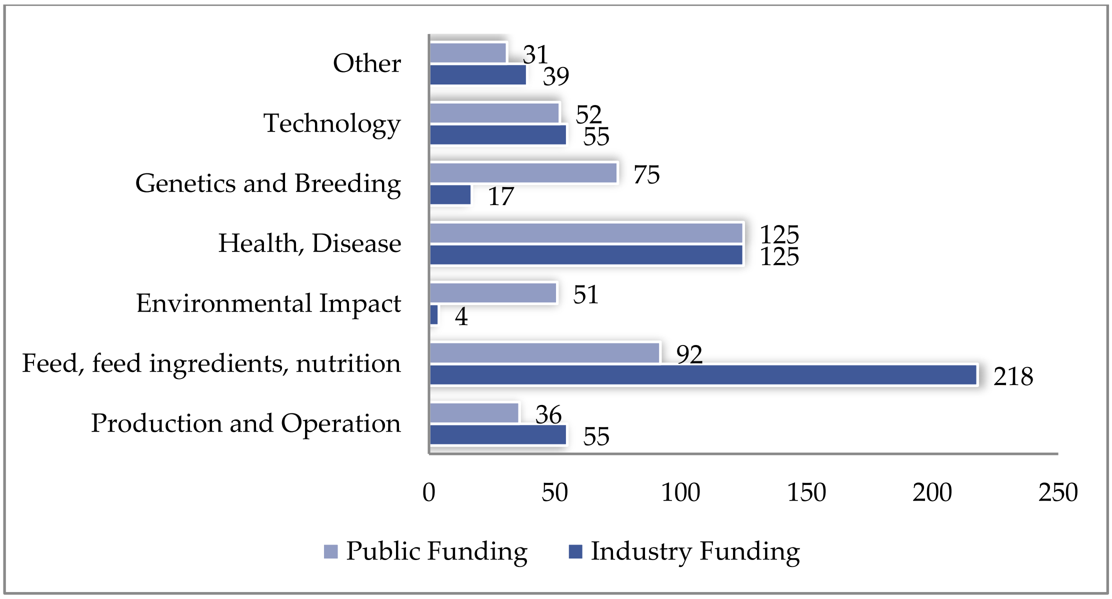


Fig 6.8 Aquaculture-related R&D in Norway, 2011 (MNok) (NIFU 2012)

The scale and intensity of knowledge-driven competition in the NASS differentiates it from other clusters in the Norwegian aquaculture sector. Not only does feed-related R&D constitute nearly a third of overall aquaculture R&D expenditures, it is also overwhelmingly industry-funded (Fig 6.8). Interviewees explained this imbalance as the result of the industry being viewed by the government as primarily self-funding.

Knowledge and learning processes

Knowledge creation in the NASS ranges from basic to highly applied. At the basic end, universities, institutes, and to some extent the feed firms explore the basic biological characteristics of salmon and new ingredients. At an intermediate level, new ingredients are tested in different conditions and new production techniques for feeds are developed. At a very applied level, specific formulas are developed with commercial product in mind.

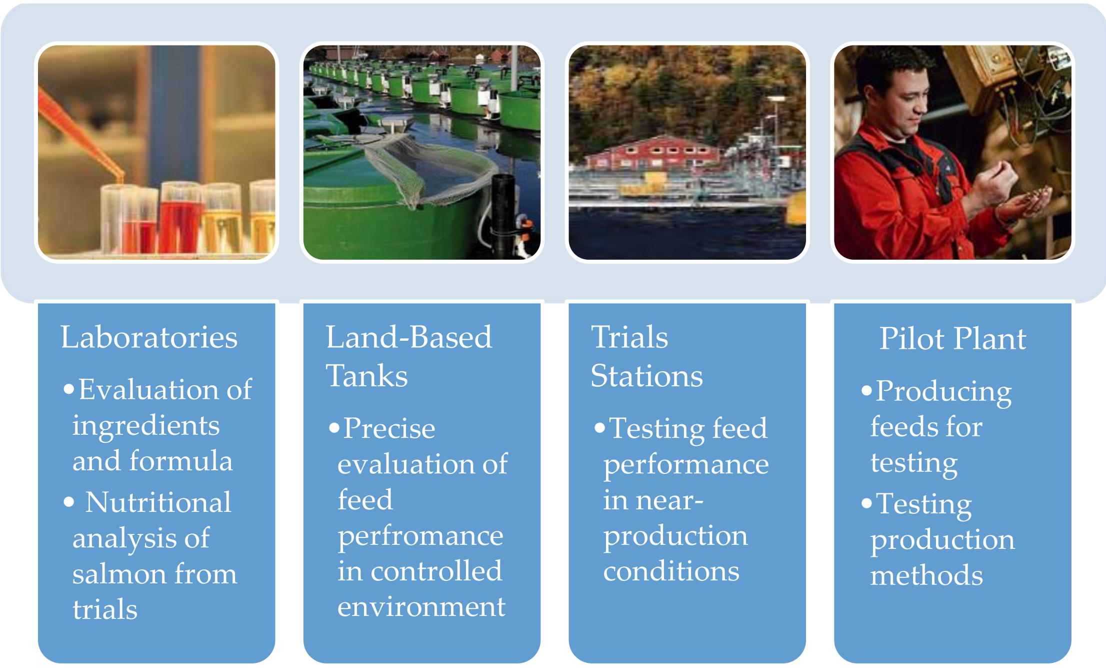


Fig 6.9 Feed Related R&D Facilities

The feed firms are known to conduct large volumes of R&D across this spectrum, with much of this has gravitating toward the applied. Because salmon feed has been traditionally been their core and most profitable market, it has been in the strategic interest of the feed producers to focus their most advanced research efforts on this area. Taking advantage of regional innovation system effects, these facilities are mostly located in Norway, even if not all research is salmon-related.

Unsurprisingly, there is a degree of secrecy in the development of sensitive DF feed technology. "We tend to do most of the DF-related research with our own funding so we don't have to publish the results," said one manager. Knowledge relating to the formulation is not easily protectable using intellectual property rights. Much of the knowledge is tacit and is best protected by retaining individuals with expertise. As a result of this competition, the internal R&D facilities of the producers rivaled, as one interviewee put it, university standards.

Nevertheless, research institutions and universities did contribute to industry projects, as they provided specialized expertise and facilities to help solve certain issues. While these collaborations facilitate learning from the knowledge network, these interactions could lead to a certain degree of leakiness with regards to sensitive information. On top of this, some interviewees found that these collaborations, especially those with universities, lacked the commercial focus of internal operations and tended to generate smaller returns on investment.

The feed firms have also collaborated with bulk ingredients suppliers, although the degree of involvement reported in interviews ranged from minimal ("They only supply samples for us to test.") to moderate. Higher levels of collaboration came from suppliers of functional ingredients.

The salmon producers themselves have become important sources of knowledge creation with regards to the use of feeds. Some of this data is derived from their use in production, but some larger producers have been known to hire research services to independently test feeds. While much of this knowledge is used to improve internal processes, feed producers have also had access to this data which provided important insights into *environmental conditions* described in the DF technology section of this report.

Institutions

The NASS today can be seen as very pragmatic and open to new technology, a progression from attitudes in the early 1990s. Among feed producers, economics and health and welfare issues are considered to be top priorities (Fig 6.10), with environmental issues being considered to a certain degree. This is somewhat mirrored by the salmon producers, albeit with a stronger emphasis on production economics (though not necessarily cost).

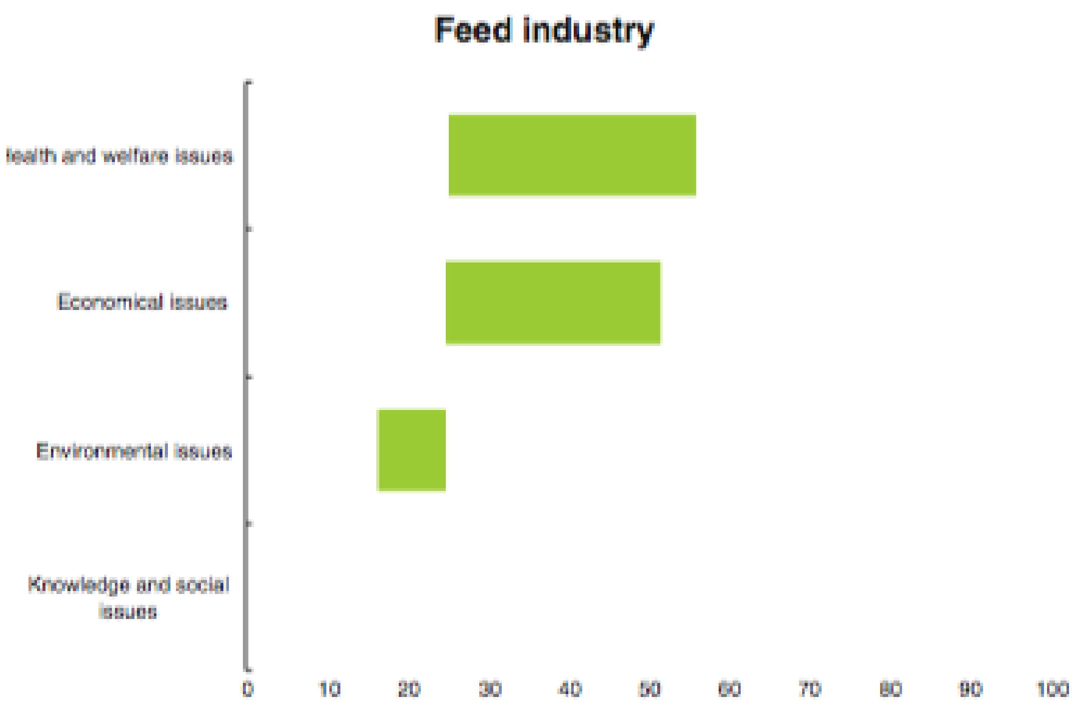


Fig 6.10 Weighting of various issues in ingredient evaluation (Gillund et Myhr 2010)

From a policy perspective, Norwegian government's direct involvement in the NASS has been rather limited. No regulations have been directly implemented to facilitate the development of DF feed, although regulations have indirectly affected it by altering demand conditions in the aquaculture SSPI.

Though represented as a priority in policy action plans, DF formulation receives significantly less public funding than what is allocated to health issues. These funds have been assigned primarily through the Norwegian Research Council, a government body created to reinforce national thematic priorities, promote international collaboration, and support basic research. One example of a project funded by the Research Council is the now-completed Aquaculture Protein Center, a Center of Excellence with a focus on long-term basic research in fields related to DF. A second and smaller body, Innovation Norway, helps fund the implementation of key technologies. A third body, the FHF, is an organization created under the mandate of the Fiskeridirektoratet to levy a research fee on exported fish products that is then allocated to research projects chosen by the industry. FHF funding, as well, was relatively low for feed research.

7. The Development of DF Technology

This section presents empirical data on the development of DF technology development within the NASS.

The Beginning

Partly because of observable benefits but also at least in part because of ingrained views, FMFO were considered to be the best ingredients in salmon farming in the 1980s and 1990s. Inclusion rates for these ingredients were at levels even higher than what was biologically necessary for the salmon themselves.

The *fishmeal trap* began to emerge as a theoretical concern among academics and a few members of the feed industry in the 1980s. This awareness set the stage for scattered instances of knowledge creation activity, mostly in the form of research projects on the impact of alternative ingredients in salmon nutrition conducted at research institutes and universities. Though the results of these experiments did little to clear the skepticism over alternative ingredients in feeds, they did form the first blocks of the DF feed knowledge base.

By 1991, there was enough concern about the issue that Skretting began a project in collaboration with Akvaforsk to screen various ingredients for their substitution potential. This was followed by another project in 1996, partially funded by the Norwegian Research Council, which focused on the effects of partial substitution of fish oil with vegetable oils on growth rates and flesh quality.

Despite these projects, the concept of substituting marine ingredients was viewed with apprehension, even among some at Skretting. While FMFO production were already starting to stagnate, for most of the 1990s price levels were not an immediate threat to salmon production. Furthermore, at that time, one of the company's main selling points for its feed was its high-grade fishmeal content and the idea that other ingredients could serve as high-quality ingredients was a direct challenge to this value proposition.

Fortunately for DF technology, Skretting was owned by British Petroleum at the time, whose focus on R&D and relative liberty of its corporate culture set it apart from other Norwegian producers, allowing the funding of unconventional projects. Following Skretting's lead, other feed companies began to undertake their own small-scale research efforts. At this time, the results of this research were not yet applicable to commercial feeds. As one interviewee put it, "We just didn't have the knowledge to produce acceptable feeds at that point."

DF feed technology received somewhat of a setback in 1996 from the Norwegian government's implementation of a quota limiting the amount of feed salmon producers could buy as a tool to limit industry-wide overproduction. This had negative short-term effects on the development of DF technology because it diverted the direction of research within the industry. Instead of developing feeds that were marine ingredient-efficient, R&D efforts focused on high FCRs at whatever cost. Since FMFO outperformed the crude plant-based feeds of the time, this incentive only reinforced their attractiveness in a market dominated by feed scarcity. The positive side of this legislation was that it did stimulate innovation in processing methods, some of which did eventually contribute to better DF technology.

A Supply Shock and a Research Boom

In 1997-1998, adverse weather precipitated by an occurrence of El Nino in the Southern Pacific decimated catch volumes of the main producers of FMFO, Peru and Chile. Fish oil was particularly affected, with prices nearly doubling in a year. By the fall of 1998, the situation had become so severe that some feed production operations shut down for lack of resources. But demand for feed from salmon producers was inflexible. Salmon take several years to raise and their biomass represents a significant investment, so feeding them to keep them alive was a priority. Faced with the prospect of the loss of salmon stocks from starvation and all of the long-term demand implications this could cause, Skretting made a decision in the middle of 1998 to produce and market all of its feed with up to 20% rape seed oil.

To reassure its clients of the safety of using plant oils, Skretting embarked in a series of communications activities, sharing data from its own experiments through industry publications. The success of these activities was rather doubtful, with farmers reporting a series of problems linked to the plant oil, many of them imagined. For example, some complaints about supposed negative effects came from farmers who were actually still using normal feeds. (ibid)

Although supplies of FMFO did return to normal levels the year after, along with vegetable oil inclusion rates, this crisis did mark a new era in the awareness about marine independence. In the following years, DF technology took on a strategic priority unknown just a few short years before. The supply shock itself convinced even the most reluctant members in the feed companies that investments in DF technology were of long-term importance. Following this trend, industry R&D activity exploded. This trend was reinforced by concerns over carcinogenic dioxins in fish oil, which made plant-based alternatives only more attractive.

Universities and research institutions were also acutely aware of the problem and were able to mobilize resources to address it as a new priority. The most visible example of this was the creation of a trans-disciplinary Aquaculture Protein Center, a collaboration between the Research Council, NOFIMA, and UMB destined to identify and develop new feed ingredients. Even outside of Norway, marine independence took on significance among relevant institutions, as reflected by increasing numbers of publicly funded projects. Being a key player in aquaculture innovation, Norway was well placed to play a key role in international projects relating to DF technology such as Aquamax and RAFOA.

DF Dominance

By the mid 2000s, DF technology had advanced to a point of what one researcher called “critical mass” as basic research started a few years earlier began to produce applicable knowledge. By this time, DF R&D had become a top priority, displacing research into pigmentation and disease control. Skretting’s 2004 annual report goes as far as citing DF technology as its main focus of innovation (Nutreco 2004). This is a position that has remained in place and can be reflected in the patterns of R&D expenditures in the industry (Fig 7.2). Mounting environmental concerns among supply chain actors, consumers, and policy makers further legitimized the pursuit of FMFO replacement around this time.

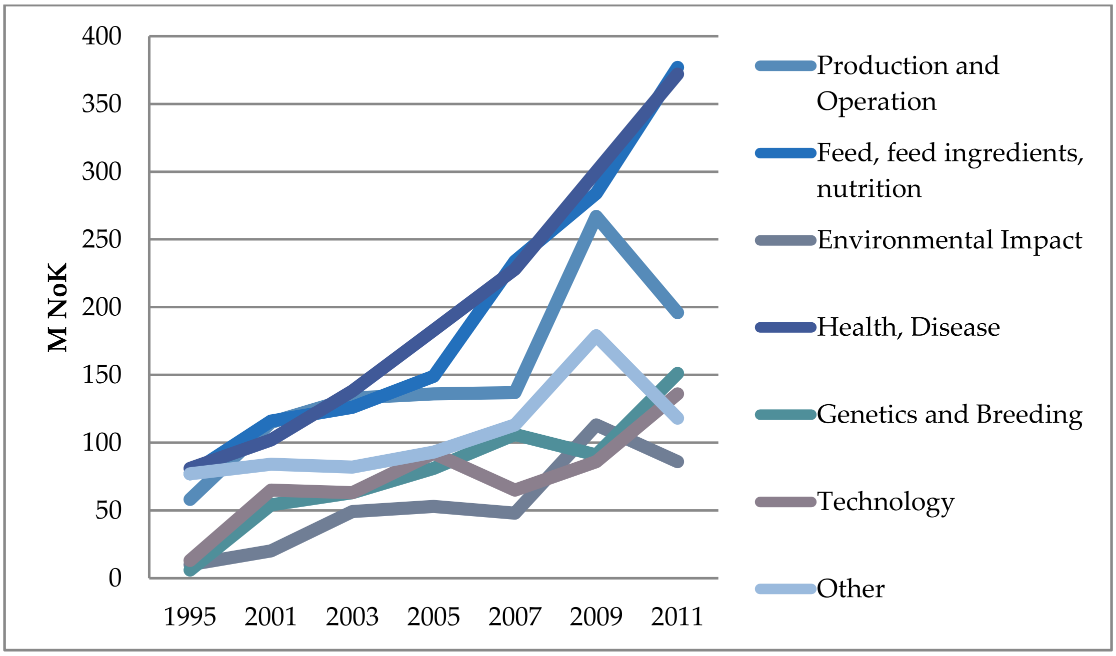


Fig 7.1 Annual R&D Expenditures in Norwegian Aquaculture (NIFU 2012)

While the feed companies did conduct early development of DF feeds despite non-articulated demand from salmon producers, continued consolidation of salmon farming activities and ever-increasing prices of FMFO changed this dynamic dramatically. As smaller, traditional companies were bought up by larger ones, increasing production volumes allowed for the specialization of labor through the hiring of highly educated individuals and improved production controls, bringing a degree of demonstrability to DF feeds with low marine inclusion rates. This trend can be reflected in adoption rates of feeds based on these technologies in the decade following the FMFO shock. In contrast with the forced imposition of mixed-oil feeds in 1998, Skretting's LipoBalance, which premiered in 2002, accumulated a voluntary market share of 55% in its first year.

The feed companies can be credited with mobilizing funding for their R&D into DF feeds, but the availability of human resources to conduct this research can be attributed to the strong education network in place in Norway. The table below shows the ability of the Norwegian education system to quadruple number of feed related university graduates in just 6 years between 2001 and 2007, filling the demand from the growing activity in the sector related to the DF TIS.

Programområde	2001	2003	2005	2007	2009	2011
Produksjon og drift: Larver, yngel, smolt	12	6	11	7	7	9
Produksjon og drift: Matfisk	7	2	8	2	8	-
Fôr, fôrressurser, ernæring	6	11	14	25	12	20
Miljøeffektstudier	1	3	11	9	2	3
Helse, sykdom	12	7	10	5	14	12
Avl, genetikk	4	3	3	10	6	6
Kulturbetinget fisk og andre kultiveringstiltak i kombinasjon mellom oppdrett og fiskeri	-	-	1	-	5	7
Teknologi, utstyr	9	1	2	1	2	5
Slakting, distribusjon, kvalitet, målemetode	2	2	1	2	8	24
Økonomi, marked, samfunn	11	11	13	4	10	11
Annet	1	-	-	14	1	15
Totalt	65	46	74	79	75	112

Kilde: NIFU

Fig 7.3 Graduate with master's degree in aquaculture-related fields (NIFU 2012)

In the last three years, Skretting began introducing feed formulations based on what they dubbed "Microbalance" technology. Building on ever more advanced knowledge of fish nutritional requirements from such scientific fields as metabolomics, these feeds used micronutrient supplementation to sink fishmeal inclusion rates to unprecedented lows. In just two years, average fishmeal rates dropped from 30% to 15%, with further decreases expected in the future. Similar technology from Ewos permitted comparable inclusion rates.

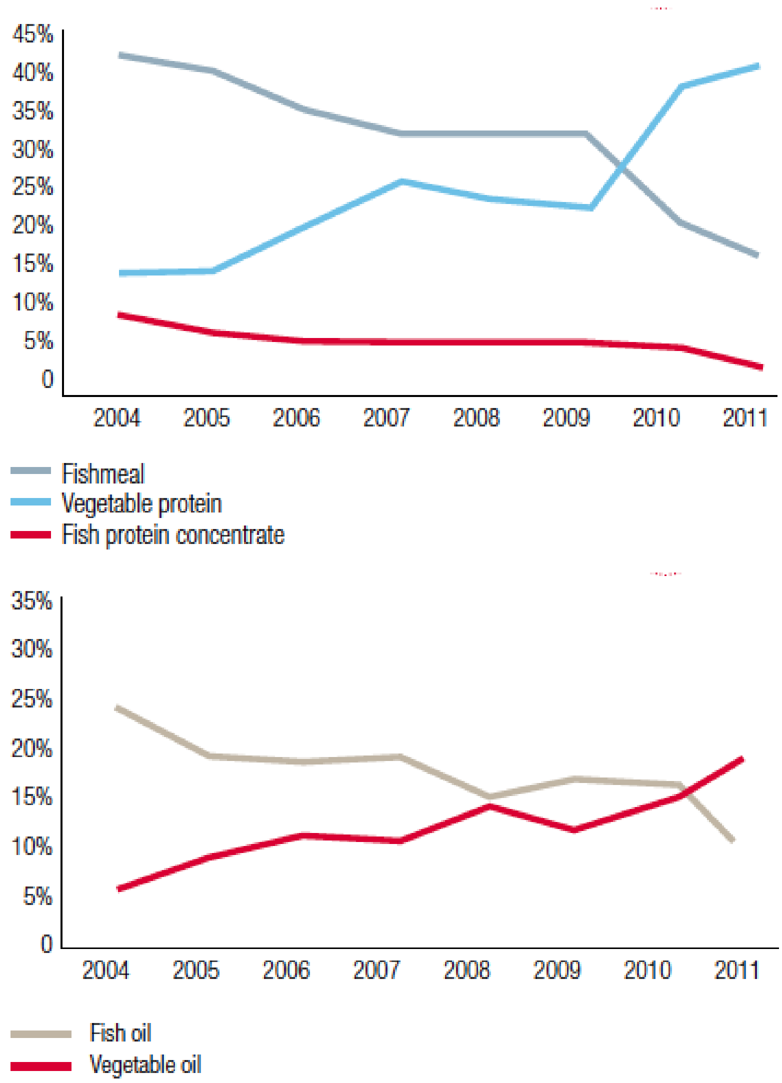


Fig 7.4 Average Inclusion Rates in Skretting feed (Nutreco 2012)

This level of substitution allowed some Norwegian operations to become net producers of marine protein, with FIFO ratios of lower than 1. Among those interviewed there was a sense of optimism regarding fishmeal independence. “We could replace even more of it if the price conditions were right,” said one. Even a representative of the FHF said he had confidence that the industry was in control of the situation.

The mood regarding innovation towards fish oil substitution was markedly less optimistic. While very substantial proportions of fish oil are now replaced with plant oils, continuing reductions are expected to erode the omega-3 fatty acid content of the salmon itself. This is seen a threat, given that salmon has historically been marketed for its health benefits. Ironically, increasing public demand for omega-3 oils based on health findings have only contributed to the problem the salmon industry is facing. In the past, salmon and other fish were the main vectors of omega-3 fatty acids for human consumption. However, the emerging supplement business, selling capsules of purified omega-3 oils, have begun competing for fish oil, which is currently the only viable source for this material.

Unfortunately, as discussed earlier, the raw material base for satisfying these omega-3 oils needs is quite limited. Interviewees identified microalgae, krill, and, most promisingly, genetically modified plant crops as being possible sources of industrial quantities of omega-3 oils. The knowledge bases and investments required to develop this technology is unfortunately beyond the scope of the feed companies, making them less engaged in the process.

For now, it seems the major efforts in this field are coming from larger agribusiness companies such as Monsanto, which is designing modified lupin oil with omega-3 oil precursors, DuPont which is researching yeast-based synthesis techniques, and other companies which still are developing micro-algae solutions. How long it would take to develop economically viable omega-3 oil sources was a matter of speculation.

Another important development was a reversal on the long-standing ban on animal by-products implemented during the BSE scare in the early 2000s. The impact of this decision, which will come into effect in the course of 2013, are not apparent just yet. One respondent considered that the logistics behind the collection of these products would limit their availability to the feed industry in Europe. A different interviewee noted the negative public opinion persisting with regards to them, especially in France where its President spoke out publicly against them. Despite these concerns, at least one company was planning to include poultry by-products as soon as the ban was lifted, citing a lack of resistance from the salmon farmers themselves.

8. Analysis

Specificities of the Norwegian Aquafeed SSPI

Based on a combination of empirical data on the Norwegian aquafeed sectoral SSPI (NASS) and secondary data gathered on those in the rest of the world, we can identify the following attributes as being rather divergent from common practices during the years over which DF has been developed:

Single Application Market

The NASS has been configured around salmon feed production for over 25 years, limiting its scope, but increasing its specialization.

Knowledge-driven Competition

Science-based feed functionality is a key performance dimension in the NASS, as opposed to many other aquafeed sectors, where cost-competition dominates.

Consolidated Producers

With 3 producers making up virtually all of feed production in the industry, the NASS is both highly consolidated and profitable

Advanced Customers

Consolidated, knowledgeable customers demand high quality feeds with certain technical attributes and generate reliable data on feed performance

Strong Knowledge Infrastructure

The NASS benefits from close proximity to a world-leading network of public and private R&D organizations specialized in aquaculture research.

Production and Downstream Regulation

The NASS is embedded in an institutional environment requiring a high degree of sustainable behavior and accountability.

While many of these attributes may be present to varying degrees in other aquafeed sectors, this particular configuration is quite uncommon outside of the NASS. In line with the descriptions of *niches* described in the *Literature Review* section, we can tentatively say that the NASS is a *niche*.

Niche Analysis

With the *niche* status of the Norwegian aquafeed sector established, we can examine its capacity to innovate as a result of these attributes. To this end, the functional analysis tool used in TIS evaluation has been repurposed for the NASS *niche.* The justification for this is that DF feeds have been central to the NASS, and many of the actors in this sectoral system would be included in a national TIS for the technology. Following this logic, the NASS can be visualized as a TIS and its *functionality* with regards to DF technology can be examined for *niche* causality.

Knowledge Creation and Diffusion (KCD)

As evidenced by its high levels of public and private R&D activity, the NASS has been highly successful with regards to KCD for DF technology. A large part of this activity can be attributed to the choices of the feed producers to locate R&D in Norway. It can also be attributed to the advanced knowledge network mentioned earlier, which was established by the Norwegian government to support the development of its aquaculture industry.

KCD in the Norwegian innovation system is remarkable for its focus on salmon feed, a *single application market*. This limited scope allowed for a degree of specialization that is sometimes lacking in other aquafeed SSPIs. Because of this intense focus, salmonids have become one of the most studied species in aquaculture, helping overcome significant bottlenecks in DF technology that might have been insurmountable otherwise.

The consolidation of Norwegian salmon farmers can also be seen as playing a role in KCD. As salmon producers became *advanced users*, they also became more adept at measuring and reporting the performance of DF feeds in production environments, sharing this information with feed producers. This type of large-scale knowledge creation is difficult for feed companies to conduct internally, and helped improve feed performance, while accelerating innovation cycles.

Influence on the Direction of the Search

FMFO supply trends have affected feed SSPIs around the world, but have had a special impact in the Norwegian aquaculture SSPI with its focus on salmon, a carnivorous fish. Modernized production methods and high proportional feed costs translated into high value-sensitivity (not to be confused with cost-sensitivity) among farmers. Furthermore, the carnivorous nature of salmon meant that they required higher levels of FMFO than many other species, making their feed especially susceptible to price fluctuations among those ingredients. The comparative advantage of Norway’s geography in salmon production and a degree of sectoral path dependency led to a certain degree of lock-in as well, preventing a large-scale switch to other fish, such pangasius, which require less FMFO to thrive.

In contrast to actors in less advanced aquafeed SSPIs, who have often responded to higher fishmeal prices by crude substitution at the expense feed performance, managers in the NASS defined FMFO scarcity as a long-term strategic challenge and not a short-term operational threat. The ability to view substitution as a question of maintaining production performance while keeping prices constant justified research undertakings in the area. Close proximity to Norway's knowledge networks and their expertise in the related fields of knowledge helped refine the *direction of the search* to match technological possibilities, improving the efficiency of R&D efforts. This managerial paradigm can be described as the *knowledge-driven competition* that is absent in many aquafeed SSPIs. Further influence on the *direction of the search* has come from the salmon producers themselves who, as advanced users with strong process control, were able to articulate their needs to feed producers.

Finally, it can be said, that growing demand for more sustainable salmon production from European consumers and regulations on ingredient use have, to a lesser extent, also shaped the *direction of the search* in recent years. These institutions are lacking in markets, such as China, where environmental issues have lacked ownership.

Resource Mobilization

The largest barriers to FMFO substitution were a lack of scientific and applied knowledge necessary to overcome technological bottlenecks. While some degree of progress might have occurred through rudimentary "learning by doing” processes, key breakthroughs came from a series of large and expensive R&D efforts funded and conducted primarily by the feed companies themselves.

Industry consolidation can be credited, in part, with marshaling the resources necessary to undertake large-scale internal R&D projects, in absence of major public funding. As resource scarcity emerged as a key landscape force, it became a strategic imperative for feed companies to devote resources to DF development. This is in contrast to many aquafeed SSPIs whose fragmented structures do not permit this scale of research expenditures. The financial attractiveness of R&D investments were only reinforced by the international presence of the feed companies, which allowed distribution of costs over secondary markets in other countries.

But the returns on R&D investments in the Norwegian feed subsector could also be traced to successfully-implemented appropriability regimes (Teece 1986). While partly attributable to the nature of the technology itself, management practices within the companies can be credited with successful retention of proprietary technology, which ensured rents on R&D investments.

A final aspect of resource mobilization relates to skilled labor, whose availability can enhance or hamper KCD functionality. The *knowledge infrastructure* of the Norwegian aquaculture SSPI can be credited with providing educated personnel to aid in DF development and also generating the level of advanced research to attract highly-skilled personnel from abroad, although the importance of these roles are harder to establish.

Entrepreneurial experimentation

Despite a lack of new entrants, the NASS has manifested a high degree of *entrepreneurial experimentation* with regards to DF among incumbent firms. This activity has been defined by a series of well-organized, science-driven projects conducted within the incumbents to explore technological opportunities. It must be noted that entrepreneurs from outside the NASS could play a stronger role in new ingredient development, although their contributions were not clearly evaluated in this study.

Market formation

The author regards DF feed as radically different in terms of performance and technology from less advanced feeds in other sectors but not as a radical innovation, per se. Current DF technology is an accumulation of hundreds of incremental improvements applied to an incumbent technology, extruded marine feeds. As such, its adoption required only relatively little adjustments in the socio-technological regime of the Norwegian aquaculture industry and faced few market formation obstacles related to reconfiguration.

Because of this, low-marine ingredient DF feeds introduced by industry incumbents were able to almost completely skip the transitional market stages and enjoy a mass market in the NASS only a few years after their introduction. It can be suggested that in absence of the need to invest resources in driving *market formation*, firms could instead devote additional resources to R&D activity.

Legitimation

This function did not seem to be a major problem for the DF technology among feed producing firms, research institutions, and governance, especially after the shock of 1998. While it's true that some *legitimation* efforts were required to overcome irrational stigma among smaller farmers against low-marine feeds, this process happened fairly quickly. Through a combination of economic attractiveness and industry consolidation, DF low-marine feeds gained market acceptance with relatively little intervention from technology champions. Like for *market formation*, the lack of a need for this function can be seen as can be seen as freeing resources for R&D.

Development of positive externalities

Capitalizing on the same institutions that had already led to the development of advanced marine-based salmon feeds, DF technology was able to benefit to some extent from many of the pre-established positive externalities, like pooled labor markets and knowledge networks, while creating a few of its own. For example, the advanced functionality of the NASS positioned it to benefit from international projects in marine independence, such as Aquamax.

Causality

Fig 8.1 shows the dynamics of functionality drivers in the NASS. While many of these were linkable to NASS niche attributes, two other factors, technological characteristics, and landscape attributes, could also be seen as influencing functionality. Technological characteristics related to the intrinsic nature of the technology and its interactions with the technological regime. Landscape factors could be considered as long-term price increases in FMFO and increasing demands for sustainability.

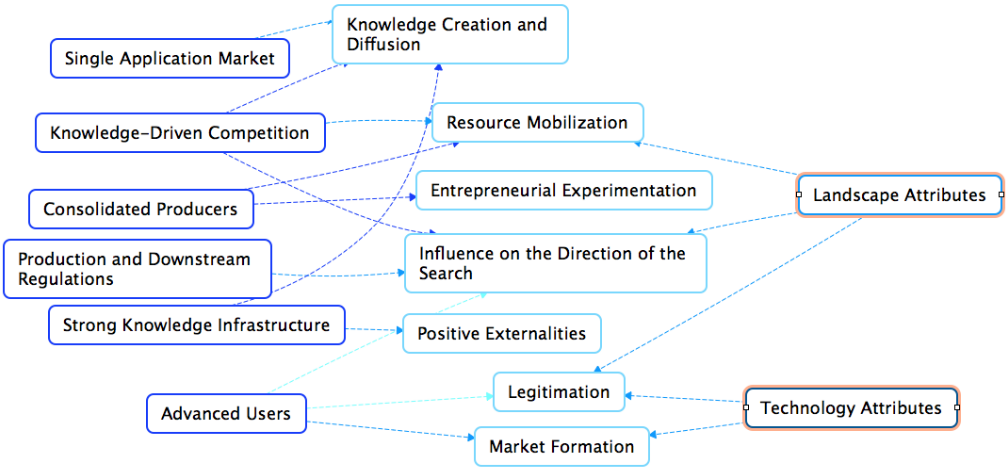


Fig 8.1 Functionality drivers

This schematic suggests that direct policy measures have had only a limited role in the functionality of this SSPI. Instead, strong incentives due to resource scarcity can be seen as a driver for DF innovation, with ideal technological and niche conditions serving as catalysts for this process. That said, government policies could definitely be credited with modernizing the industry and establishing a knowledge-based network pre-existing DF development. In this light, we can see the functionality of the system with regards to DF as a secondary positive externality of previous policies.

It must be stressed that any environmental benefits of DF technology have also been more a positive externality than a driving force for innovation. It is simply coincidence that the diffusion/use of this technology aligns with sustainability issues. This means that within the NASS, this case should not be viewed as an example of market failure.

10. Conclusion and Comments

Can niche conditions within an SSPI generate sustainable technology without direct government intervention?

From this analysis, the author concludes that in the case of the NASS, the successful development of DF technology was directly attributable to niche conditions, which were only indirectly the result of government policies. While evaluations of the environmental impact of DF technology range from positive to neutral, its contribution to the long-term economic sustainability of the Norwegian salmon industry is indisputable. Therefore, it may at least be concluded niche conditions within an SSPI can improve its innate capacity to mount innovation responses to systemic threats. However, the role of the government in making long-term investments in infrastructure, which may take several decades to come to fruition, cannot be neglected either.

Besides these conclusions, there are many other interesting aspects of the NASS and its relationship with DF technology which were raised during this study but could not be addressed within the scope of the research question.

So far, DF feeds, and even high-performance extruded feeds have not achieved the same level of diffusion in other aquaculture production regimes as they have in Norway. However a “landscape” shift could create the right conditions for the diffusion of DF technology within the patchwork of other aquafeed socio-technical regimes. FMFO prices are expected to increase in the long run, and with them, the economic attractiveness of DF aquafeeds compared to crude, locally produced feeds. Along with a growing demand for quality among export markets is an increasing demand for environmental accountability, which could make unsustainably sourced marine ingredients, like trash fish, off-limits to producers in countries like Thailand.

These landscape factors are destabilizing existing production regimes in aquaculture sectors dominated by extensive aquaculture techniques, and could lead to an occurrence of the multi-level *technological substitution pathway* (Geels et Schot 2007), as DF technology progressively diffuses from its niche. There are already signs that this is starting to happen as firms like Skretting acquire operations in Asia and South America that cater to other species such as pangasius and even shrimp, and adapt the technological platform of salmon DF feeds to the needs of these species. Needless to say, these feeds are based on vast amounts of R&D investments and outperform those based on the limited technology of endemic producers on many fronts. As these sectoral systems align with those of Norway, DF feed technology could become widespread in other commercially fed species.

Another topic of discussion could be *niche management*. While the huge strides of Norwegian aquaculture towards marine independence has been impressive, the relative lack of collaboration among the major aquafeed companies may serve as a hindrance to its innovative capabilities. Research duplication among the big 3 producers could be seen as a less than optimal allocation of resources. More ominously, these innovation patterns have limited *resource mobilization* for the very large-scale projects that will be needed to address future threats to food security and hindered information flows. Collaboration does not necessarily erode competition, and in much the same way that consolidation of industry structure led to current advances, a pooling of resources on a sectoral scale could lead to breakthroughs inaccessible to any single company.

A case in point, the imminent omega-3 oil shortage is far from being resolved. This may not be a failure, per se, of the current NASS but it does represent an opportunity for closer collaboration among the feed firms. While one instance of collaboration between all three producers on the issue was identified, for now, it appears as if the ownership of the issue has been delegated to actors outside of the NASS.

But that challenge is still relatively minor compared to that posed by climate change on the production of plant-based ingredients. Norwegian salmon production may be inching towards being a net producer of marine protein yet it still is far from being a net producer of nutrients when compared to wholly vegetarian diets. Though not technological possible at the present time, the potential to convert raw materials that that have little use as human foodstuffs directly into protein sources, could make salmon production into a *net nutrient producer*. Two scenarios of this would be insect meal technology and multi-trophic aquaculture, both of which could theoretically be used to recycle nutrients by retrieving them from waste that would otherwise pollute the environment.

This observation opens the door for investigation of a stronger role of the Norwegian government in the NASS. While not necessarily advocating increases in public funding, the author could envision the utility of policy incentives destined to promote greater levels of collaboration among actors. The author realizes that this is a delicate subject, but believes that it may be interesting to examine the Norwegian sector using a *niche management* approach. Ideally, this exploration could lead to the implementation policy instruments that bolster the positive externalities of the NASS beyond the aquaculture sector and into global food security.

11. Bibliography

Ytrestoyl, and et al. *Resource utilisation and eco-efficiency of Norwegian salmon farming in 2010.* Tromso: Nofima, 2011.
Asche, Frank, Atle Guttormsen, and Ragnar Tveteras. "Environmental problems, productivity and innnovations in Norwegian salmon aquaculture." *Aquaculture Economics & Management* 3 (1999): 19-29.
Asche, Frank, Kristin Roll, and Ragnar Tveteras. *Journal of Environmental Economics and Management*, 2009: 93-105.
Aslesen, Heidi Wiig. "The Innovation System of Norwegian Aquacultured Salmonids." In *Innovation, Path Dependency, and Policy: The Norwegian Case*, by David Mowery, and Bart Verspagen Jan Fagerberg. Oxford University Press, 2009.
Arnold, E., K. Guy, and M. Dodgson. "Linking for Success:Making theMost of Collaborative R&D. London: National Economic Development Office/Institution of Electrical Engineers." 1992.
Baragheh, Anahita, Jennifer Rowley, and Sally Sambrook. "Towards a multidisciplinary definition of innovation ." *Management Decision*, 2009: 1323-1339.
Bergek, Anna, Staffan Jacobsson, Bo Carsson, Sven Lindmark, and Anni Rickne. "Analyzing the functional dynamics of technological innovation systems: A scheme of analysis." *Research Policy*, 2008: 407-429.
Carlsson, B, and R Stankiewicz. "On the Nature, Function, and Composition of TEchnological Systems." *Journal of Evolutionary Economics*, 1991: 93-118.
CONICYT - Chile. *The fishery and aquaculture sectors in Chile.* Santiago de Chile: National Commission for Scientific and Technological Research, 2007.
Cooke, Philip, Mikel Uranga, and Goio Etxebarria. "Regional innovation systems: Institutional and organisational dimensions." *Research Policy* 26, no. 4-5 (1997): 475-491.
Dodgson, Mark, David Gann, and Ammon Salter. *The Management of Technological Innovation.* Oxford: Oxford University Press, 2008.
FAO. *Aquaculture Development in China: The Role of Public Sector Policies.* FAO, 2003, 9.
FAO. "Demand and supply of feed ingredients for farmed fish and crustaceans - Trends and Prospects." Fisheries and Aquaculture Technical Paper, Rome, 2011.
FAO. *Food Security.* Policy Brief, FAO, 2006.
FAO. "THE STATE OF WORLD FISHERIES AND AQUACULTURE." Fisheries and Aquaculture Department, 2012.
Fiskeritdirektoratet. *Norwegian Directorate of Fisheries.* 2012.

Geels, F.W. "Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective Technological Forecasting and Social Change, Volume 72, Issue 6, July 2005, Pages 681–696." 2005.
Geels, Frank, and Johan Schot. "Typology of sociotechnical transition pathways." *Research Policy* 36, no. 3 (April 2007): 399-417.
Gillund, Froydis, and Anne Myhr. "Perspectives on Salmon Feed: A Deliberative Assessment of Several Alternative Feed Resources." (Spring Science+Business Media) January 2010.
Huntington, Tim, and Mohammad Hasan. *Fish as feed inputs for aquaculture – practices, sustainability and implications: a global synthesis.* FAO Fisheries and Aquaculture Technical Paper, Rome: FAO, 2009, 1-61.
Hekkert, Suurs, Negro, Kuhlmann, Smits. "Functions of Innovation Systems: A New Approach for Analysing Technological Change." *Technological Forecasting & Social Change* 74 (2007): 413-432.
HLPE /FAO. *Price volatility and food security.* Rome: FAO, 2011.
Hoogma. "Regime shifts to sustainability through processes of niche formation. The approach of strategic niche managementTechnol. Anal. Strateg. Manag., 10 (2) ." 1998.
Hoogma, R. "Experimenting for Sustainable Transport. The approach of Strategic Niche Managment." (Spon Press) 2002.
Lundvall, B.A. "Innovation as an Interactive Process: User-Producer Interaction to the National System of Innovation." 2009.
NBSO. *An overview of China's aquaculture.* Dalian: Netherlands Business Support Office, 2010.
Nelson, R, and S Winter. "An Evolutionary Theory of Economic Change. The Belknapp Press of Harvard University Press, Cambridge." 1982.
NIFU. *Marin FoU og havbruksforskning 2011.* NIFU, 2012.
Malerba, Franco. "Sectoral systems of innovation and production." *Research Policy* 31, no. 2 (2002): 246-264.
Marine Harvest. *Salmon Farming Industry Handbook 2012.* Marine Harvest, 2012.
Maroni, K. "Monitoring and regulation of marine aquaculture in Norway." *Journal of Applied Ichthyology* 16, no. 4-5 (2000): 192-195.
Merriam Webster. *Merriam-webster.com.* http://www.merriam-webster.com/dictionary/technology (accessed April 12, 2013).
Quintane, Eric, Mitch R Casselman, Sebastian Reiche, and Petra Nylund. "Innovation as a knowledge-based outcome ." *Journal of Knowledge Management*, 2011: 928-947.
Pauly, Daniel. "Anecdotes and the shifting baseline syndrome of fisheries." *Conservation Letters*, 1995: 93-100.
Pavitt. "K. Pavitt Patterns of technical change: towards a taxonomy and a theory Research Policy, 13 (1984), pp. 343–374." 1984.

Perlman, Hanni, and Francisco Juarez-Rubio. "Industrial Agglomerations: The Case of the Salmon Industry in Chile." *Aquaculture Economics & Management* 14, no. 2 (2010): 164-184.
Schilling, Melissa A. "Strategic Management of Technological Innovation." 2010.
Shepherd, J. 2009.
Sorensen, Mette, et al. *Today's and tomorrow's feed ingredients in Norwegian aquaculture.* Tromso: Nofima, 2011.
Roberts, E. "Benchmarking Global Strategic Management of Technology." *Research Technology Managmeent*, 2001: 25-36.
Tacon. 2008.
Tacon, Albert, and Marc Metian. "Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects." *Aquaculture* 285, no. 1-4 (2008): 146-158.
Talbot, C. & Rosenlund, G. "Learning from the salmonid industry growing fish on nutrient-dense diets." *Aquafeed International*, 2002: 7-10.
Teece, D.J. "Profiting from technological innovation: Implications for integration, collaboration, licensing, and public policy." *Research Policy*, 1986.
Truffer, Berhard, and Jochen Markard. "Technological innovation systems and the multi-level perspective: Towards an integarated framework." *Research Policy* 37 (2008): 596-615.