Innovations and Productivity Performance in Salmon Aquaculture

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Abstract. Since the 1980s a large number of innovations have radically transformed the production process in salmon aquaculture. Increased degree of control with the production process, increased scale of plants, and more intensive use of farm locations are some of the consequences. Until the mid 1990s the industry also experienced rapid productivity growth leading to production costs to be reduced to 1/3 of their initial levels in Norwegian salmon aquaculture. But thereafter productivity has been stagnant. This paper analyses the innovation process and productivity growth in the Norwegian salmon industry, and discusses the challenges for the future.

Keywords: Innovation, productivity growth, salmon aquaculture, translog cost function.

1 Introduction

A growing global population requires increased production of marine proteins, and this can only come from aquaculture since global wild fish stocks are generally fully exploited or over-exploited [1]. Consumers will not only demand more seafood but also increased product quality and diversity as they become wealthier [2]. Aquaculture is better positioned than fisheries to provide the product quality and diversity that future consumers will demand. But with scarce farming areas, high local environmental impacts and limited marine feed raw material sources global aquaculture cannot continue to expand with current technologies. Aquaculture sectors need to innovate in several key areas to be able to satisfy the increasing global demand for seafood [3]. This is also the case for salmon aquaculture, one of the technologically leading sectors.

Our study focuses on salmon aquaculture, which has increased its degree of control with the production process through many innovations in key technologies such as fish feed, feeding equipment, IT based monitoring of live fish, vaccines and genetics [4], [5], [6]. Salmon production has moved from a technological regime with poor degree of control of many processes to one that can be described as approaching 'biological manufacturing'. Many of the tasks that before was manual, such as fish monitoring, fish feeding, fish harvesting and equipment maintenance, have now been automated to a large extent. This has contributed to significantly increasing productivity and improving the quality of farmed salmon since the 1980s.

This paper discusses the past innovations and accompanying productivity effects (section 2), estimates how the rate of technological progress changes over time in salmon aquaculture using an econometric cost model specification on a large data set of salmon firms, and links the estimated rates of technological change over time to innovations in key technology areas (section 3). Finally, the paper discusses the future innovation challenges for the salmon industry, several which it share with other aquaculture sectors (section 4).

2 Innovations and the Innovation System in Salmon Aquaculture

Innovations in salmon aquaculture include technology areas such as feed, fish health and equipment, but also regulatory innovations. Examples of innovations are presented in Figure 1.

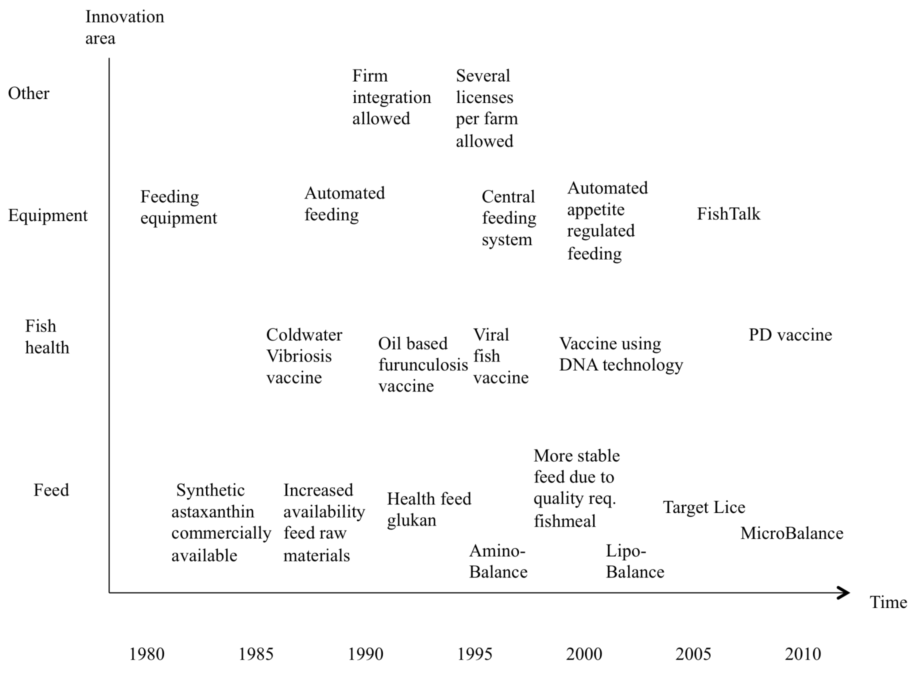

Fig. 1. Examples of innovations in salmon farming over time

As a consequence of these innovations, salmon aquaculture has evolved from a technological regime with poor degree of control of many processes to one that can be described as approaching 'biological manufacturing' [4], [5], [6]. The industry has moved from a labor-intensive production where workers had few formal skills, to a production which is more capital-intensive and where computer hardware and software based technologies have replaced several of the manual tasks of labor. At the farms the monitoring of the salmon, feeding, and environmental variables are based on sophisticated information technologies. Labor input has become more specialized; workers now tend to have certificates, and there is a much higher proportion of labor with a variety of specialized university educations.

Salmon feeds, which represent over 50% of farms' production costs, have experienced radical innovations partly due to large investments in R&D. Formulation of salmon feeds are now based on extensive knowledge of how different ingredients influence salmon growth and health and interact with each other. R&D has also played a significant role in disease management, where a number of targeted vaccines have been developed to combat various diseases. To some extent these have replaced curative medication such as antibiotics. Salmon farming now uses much less antibiotics per kilo of meat produced than is the case in terrestrial meat production such as pork and poultry.

Innovations in key technologies have contributed to a significant productivity growth in salmon farming. The cost of producing farmed salmon has declined to less than 30% of production costs in the late 1980s, as shown later in Figure 3. However, productivity growth in the salmon industry as measured by the cost of production per kilo of live salmon has stagnated in the recent decade.

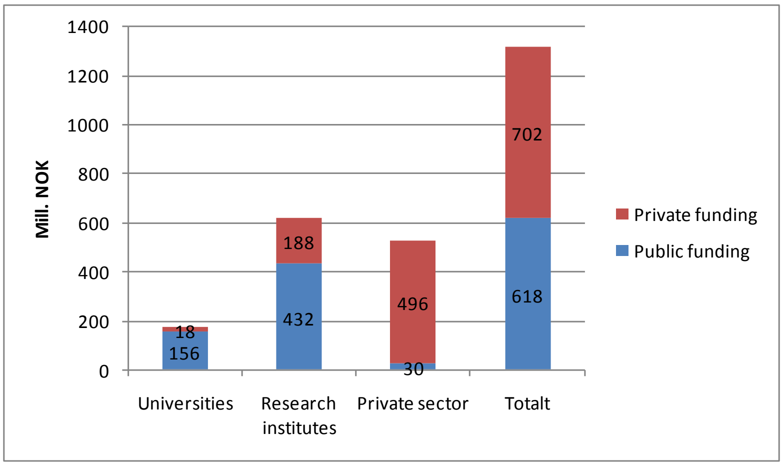

Fig. 2. R&D by performing sector and funding source in million Norwegian kroner (Source: NIFU-Step)

In the innovation system [7], [8] related to salmon aquaculture technology the Norwegian government, particularly the Ministry of Fisheries, has been a central actor through legislation, policies and funding. A technological innovation system can be defined as 'a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology' [9]. The private actors in the innovation system include the salmon farming companies and their suppliers, feed companies, equipment and software suppliers, pharmaceutical companies, etc. Universities have also been important actors both as suppliers of trained labor and researchers, but also through the R&D they have undertaken. Independent research institutions that are predominantly funded by the public sector is another group of actors that have played a pivotal role through their R&D activities.

Many innovations in salmon aquaculture that have contributed to productivity growth have been made possible by R&D that has been at least partly funded by the Norwegian government. The public sector has played an active role both in financing and in carrying out R&D through public research institutions and universities. In the private sector fish feed companies and pharmaceutical companies have also played important roles in financing and carrying out R&D related to salmon feed, fish health, vaccines etc. According to Figure 3 the private sector funded 53% of R&D in aquaculture in 2009, and did around 40% of the R&D activities, while the remaining 60% was undertaken by universities and research institutions.

Salmon farming companies have historically played a smaller direct role in undertaking and financing R&D themselves. Initially, the industry was dominated by small companies with limited financial and human resources. Their role in innovation processes was often to adopt innovations made by suppliers to the industry, such as feed companies, equipment suppliers and pharmaceutical companies. However, the industry has since the early 1990s developed an industrial structure which also includes large scale multinational companies. Salmon companies should be expected to have a more prominent role in future innovation processes due to industry consolidation that should increase their ability to both finance and manage R&D.

3 Estimation of Productivity Growth

In this study we estimate the rate of technological change in salmon farming. This is done by econometric estimation of a translog cost function on a data set of 4904 observations on individual salmon firms from 1985 to 2008. We are able to separate the effects of input prices, scale economies and technical change on real costs.

The long-run translog cost function is specified as:

$$\begin{aligned}\ln C = \alpha_0 + \Sigma_i\alpha_i\ln w_i + 0.5\Sigma_i\Sigma_j\alpha_{ij}\ln w_i\ln w_j + \alpha_y\ln y + 0.5\alpha_{yy}(\ln y)^2 \\ + \Sigma_i\alpha_{iy}\ln w_i\ln y + \Sigma_t\alpha_t D_t + \Sigma_t\Sigma_i\alpha_{it}\ln w_i\cdot D_t + \Sigma_t\alpha_{yt}\ln y\cdot D_t + u.\end{aligned} \tag{1}$$

In this model C is inflation-adjusted cost of production, y is output level, w_i is the inflation-adjusted price of input i (i = Feed, Labor, Capital), D_t is a vector of time (year) dummy variables (t = 1986, …, 2008) for the years after the base year 1985, u is a stochastic error term, and α are parameters to be estimated. To improve the efficiency of the parameter estimates, the cost function is estimated together with the cost share equations $S_i = \partial\ln C/\partial\ln w_i$, using Zellner's [10] seemingly unrelated regression technique. The above econometric model specification allow us to decompose technological progress into three components: (1) neutral ($\Sigma_t\alpha_t D_t$), (2) input biased ($\Sigma_t\Sigma_i\alpha_{it}\ln w_i\cdot D_t$), and (3) scale biased ($\Sigma_t\alpha_{yt}\ln y\cdot D_t$) components. The rate of technical change (TC) with these three components is specified as:

$$TC = (\alpha_t - \alpha_{t-1}) + \Sigma_i((\alpha_{it'} - \alpha_{it-1})\ln w_i) + ((\alpha_{yt'} - \alpha_{yt-1})\ln y). \quad (2)$$

If there is technical "progress" this cost based measure is negative. The rate of technical change is our measure of how innovations and other factors influence productivity growth. It is not possible to obtain a "pure" measure of the effects of innovations as it is hard to identify variables that measure innovations and the adoption of these. Moreover, in a biological production sector such as salmon farming the TC measure will also be influenced by biophysical shocks such as diseases. It is therefore possible to obtain negative rates of technical change.

From the cost function one can also derive returns to scale, which are defined as $RTS = 1/(\partial \ln C/\partial \ln y)$. The conditional own price elasticity of demand for input i is defined as $E_i = (\alpha_{ii} + S_i^2 - S_i)/S_i$ (i = Feed, Labor, Capital) [11].

Table 1 presents sample mean elasticity estimates from the estimated translog cost function. The full set of parameter estimates can be obtained from the authors. Sample mean returns to scale (RTS) is increasing with a value of 1.152. The conditional own-price elasticities (E_i) all have the expected negative sign, with feed input having the lowest elasticity. They are within the range of estimates from previous econometric studies of Norwegian salmon farming [6], [12], [13], [14].

Table 2. Sample Mean Elasticity Estimates from Estimated Translog Cost Function*

Variable	Mean	St.Dev.	Min	Max
RTS	1.152	0.076	0.924	1.527
E_{Feed}	-0.155	0.045	-0.329	0.018
E_{Labor}	-0.387	0.210	-0.435	12.124
$E_{Capital}$	-1.062	0.052	-1.256	-0.913
TC	-0.034	0.060	-0.257	0.247

*No. of observations is 4904, except for TC (N=4723) due to omission of observations in 1985.

Our main variable of interest is the rate of technical change. According to Table 1 the overall sample average rate of technical change is -0.034, i.e. an annual average 3.4% rate of technical progress.

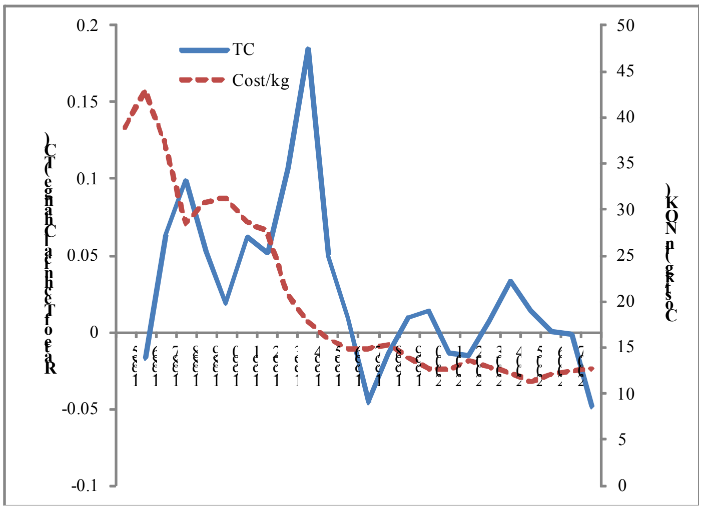

Fig. 3. Production cost including feed, labor and capital per kg produced fish (Cost/kg) and the estimated rate of technical change (TC).

However, this technical progress varies considerably over time, as shown in Figure 3, where we have plotted the development in the annual average rate of technical change (the negative of TC) together with the development in real production costs including feed, labor and capital. We see that the highest rates of technical progress were experienced from 1987 to 1995. After that technical progress, as measured by our econometric model, has been low. This is mirrored in the development in real production costs per kg produced fish, which declined rapidly until the middle of the 1990s, but has since experienced a much smaller decline, and been more or less stable around 12-13 NOK/kg since 2000.

An important explanatory factor behind the decline in technical progress is the inability to reduce salmon mortality rates, which have fluctuated around 20-30% of the stock of live salmon since the 1990s. The growth in salmon production has lead to an increase in disease pressure among the fish, as fish population densities have increased both at the regional and farm site level. The salmon industry has not been able to innovate sufficiently fast to reduce disease losses. Innovations in automation, such as automated feeding and fish monitoring, and other areas have contributed to increasing production per employee by several times the levels in the 1990s. But this has not been sufficient to compensate for the lack of innovations in fish health and disease management.

4 Future Innovation Challenges

The future technological bottlenecks that need to be resolved in global aquaculture in general and salmon aquaculture in particular will be more complex than those faced historically. One can argue that each of the bottlenecks on average will require higher investments in R&D, reflecting more input of researcher man-hours and higher expenditures on equipment and materials. Furthermore, the R&D projects will have a higher level of technical and organizational complexity, and thus increased risk of failure or low returns to R&D investments. The implications of these assertions is that in order to produce innovations at a sufficient rate, the industry needs higher D&D funding and increased quality of human capital involved in the R&D projects, and the organization of the projects.

In order to understand important aspects of the innovation challenges salmon aquaculture faces it is necessary to understand the nature of innovation processes in the industry. The innovation literature distinguishes between two modes of innovation. One, the 'Science, Technology and Innovation' (STI) mode, is based on the production and use of codified scientific and technical knowledge. The other, the 'Doing, Using and Interacting' (DUI) mode, relies on informal processes of learning and experience-based know-how [9]. One can find many examples of both modes of innovation in salmon aquaculture. But it can be argued that STI based innovation processes generally have led to more radical innovations than DUI processes in salmon aquaculture. This is the case for several innovations related to e.g. feed and vaccines. Also in the future should we see both modes of innovation. However, the more radical innovations that the industry needs to increase its productivity and grow have to be based on STI processes. But it should be pointed out that STI processes can have different characteristics, including what types of agents fund R&D and what types of agents perform the R&D activities. For Norwegian salmon aquaculture a major actor in selection and funding of research projects has been the government's Norwegian Research Council (NRC), a body dominated by scientists from academia, where projects have been largely selected on the basis of the academic credentials of the applicants. Publication of results in international peer-reviewed scientific journals have generally been regarded as an important indicator of success for NRC funded projects, and innovation outcomes have received less attention. Innovations in salmon aquaculture have often been based on results from NRC funded projects, but have been made in separate, later projects with commercialization objectives.

There may to some degree be complementarities between the research focused on creating new knowledge and publication in peer-reviewed journals funded by the government through the NRC and R&D funded by the private companies with more direct commercial objectives. However, one important question for the future is who should decide on the allocation of NRC funding – how much influence should the academic sector have and how much influence should private sector have in the formulation of NRC research program objectives and selection of projects? Until recently the dominance of academia can be explained by the lack of sufficiently trained candidates from the private sector. But the private sector is increasingly recruiting employees with scientific training, and this should facilitate a change in the balance between the academic and private sector in the future.

In the future innovations are required in all key technology areas. For salmon feed, which represents over 60% of total costs, it is necessary to continue the replacement of scarce marine ingredients with vegetable ingredients to reduce ingredient costs. The industry faces several salmon diseases which require improved vaccines and other strategies to reduce mortality. There are also other more environmental challenges which may not affect productivity directly, but will have consequences for the industry's ability to expand, as future expansion is dependent on its environmental impacts. Salmon farm cages and other structures need to be further improved to reduce the likelihood of salmon escaping. Innovations are also required to reduce the presence of salmon lice in the surroundings of salmon farms.

It is necessary to increase the productivity of salmon aquaculture R&D in the sense that it should lead to more innovations per million Norwegian kroner invested in R&D. R&D financed by the government and undertaken by government institutions have been highly necessary in the past to develop key technologies. But in the future it may be essential to have greater proximity between those who finance and undertake R&D and the industry to increase the innovation rate. This is to an increasing the degree possible as the industry itself has much greater financial and human resources today than in the past to finance, manage and undertake R&D.

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