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Farming the Sea

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Abstract *During the last decades aquaculture has been one of the world's fastest growing food production technologies. This is primarily due to increased control over the production process that has enabled innovations, productivity growth, and reduced production costs. Compared to agriculture, production technology, research, and development in aquaculture are still not very sophisticated and control over the production process is still limited. This implies that there still is potential for further innovations and productivity growth in aquaculture. Although one must face similar environmental challenges as agriculture, there is no doubt that intensive aquaculture can be sustainable. Moreover, increased food production from the sea can reduce pressure on marginal terrestrial land and deforestation. As the productivity potential in aquaculture is exploited, aquaculture production is set to continue its increase, and humanity will, to an increasing extent, also farm the sea.*

Key words Aquaculture, farming, innovation, productivity.

JEL Classification Codes Q18, Q22.

Introduction

Water covers more than three quarters of our planet's surface. Although from distant history humanity has harvested the oceans', lakes' and rivers' surplus production, our use of the earth's waters as a source for food has been essentially the same to the present day. It has been a passive harvesting activity, fishing, of its surplus production. Too often, the surplus production has not been enough, and the production base has been fished down; *i.e.*, the fish stocks. This is largely in contrast to what has happened with terrestrial food production, where domestication and innovation has led to a significant increase in food production, supporting a growing population. However, if humanity is to exploit the earth's food production potential, one must also exploit the vast expanses of the planet that are covered by water. One must farm the sea. Aquaculture holds this potential, but it is still in its infancy as a large-scale food producing industry.

During the last decades, aquaculture has become an increasingly important source of seafood. Aquaculture production has increased from 3.5 million tonnes in 1970 to about 63 million tonnes in 2005 (see figure 1 in Asche, Guttormsen, and Tveteras (2008) for a graphic representation of the development). In 2005, aquaculture made up 40% of the 157.5 million tonnes of seafood that were produced, and from the early 1990s it is the increased supply from aquaculture that has maintained

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the increasing trend in the world's seafood supply. In fact, the per capita availability of seafood has increased slightly during the last decades, primarily due to increased supply from aquaculture. If one looks at seafood for human consumption, aquaculture production is now as important as wild fisheries. Moreover, with an annual average growth rate of 7.8% since 1970, aquaculture is the world's fastest growing food production technology (FAO 2006).

Hence, it is already clear that aquaculture is an important source of seafood, and it is possible to argue that humanity is already farming the sea. However, as aquaculture has supplied significant quantities of seafood only during the last few decades, it is still a very young industry. More importantly, while there has been substantial development in biological knowledge and technology, the industry is, in this respect, still in its infancy compared to many other food producing industries. This also implies that there is still tremendous potential for further growth in aquaculture. It is accordingly of interest to reflect on the dramatic changes in aquaculture during the last decades and what they implies for the future. This article will argue that the aquaculture industry is still in its infancy and that there is still a long way to go before one is truly farming the sea.

The key difference between aquaculture and fisheries is the control the farmer has over the production process (Anderson 2002). Aquaculture can be defined as the human cultivation of organisms in water. As such, it is in principle more similar to forestry and animal husbandry than to traditional capture fisheries. In other words, aquaculture is stock cultivation rather than hunting. The aquaculture production process is determined by biological, technological, economic, and environmental factors. Most aspects of the production process can be brought under human control. It is this control that makes innovation possible, and this control is essential for the rapid technological development that has fuelled production growth in aquaculture that began in the early 1970s.

At times it can be hard to separate aquaculture from wild fisheries. For instance, how much effort must an oysterman put into the maintenance of his oyster beds before it becomes aquaculture? Anderson (2002) argues that a continuum of production modes stretches from a high degree of control in intensive aquaculture to basically no control in unregulated fisheries. However, aquaculture technologies with very limited control over the production process will be inefficient and have little scope for innovation. Hence, they are of limited interest if one is to farm the sea, rather than just harvest its surplus production.

Although aquaculture is a very old food-producing technology, it was not very important in terms of quantity produced until the 1970s. At that time a revolution occurred with the introduction of semi-intensive and intensive farming practices; *i.e.*, producers started to more actively influence the growing conditions of the fish with feeding, breeding, *etc*. The control of the production process that was achieved allowed a number of productivity-enhancing innovations to take place. Improved productivity implies a reduction in production costs, and with a given price, this makes production more profitable. High profits are the market's signal to increase production, and this will happen both because existing producers produce more and because new producers enter the industry. To sell the increased production, one needs to give the consumers a reason to buy the product, and in general the most important incentive used is a price reduction. A substantial part of the cost savings due to productivity increase is passed on to the consumers in the form of lower prices, as this makes the aquaculture product more competitive relative to other food sources.

The most important drivers in the development of modern aquaculture can be summed up as follows: Control over the production process allows technological innovations that reduce production cost. This makes the product more competitive and the industry profitable, leading to increased production and lower prices for the consumers. This is shown for farmed quantity of salmon and the real Norwegian export price in figure 1, and for globally farmed quantity and real US import price for shrimp in figure 2. One can say that this development is not specific to aquaculture, and indeed it is not. It is basically what happens with any rapidly growing industry. For instance, Gardner (2002) provides a detailed description of the development in US agriculture where productivity growth leads to increased consumption and lower prices. Growth can then be further amplified if demand increases as more consumers find that this is a product they need, but the basic mechanism is anyway the same.

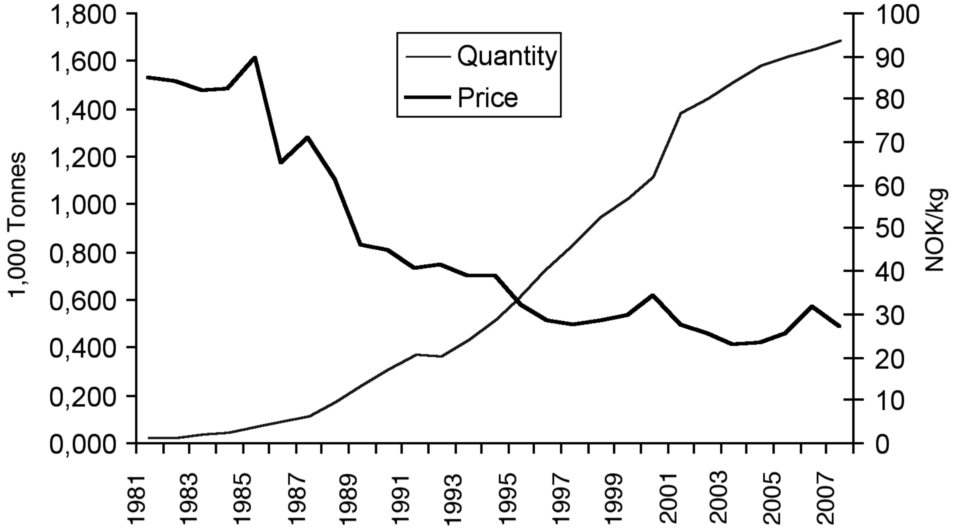

Figure 1. Global Salmon Production and Real Price, 1981–2007 (2006=1)
Source: FAO (2008b); Norwegian Seafood Export Council (2008).

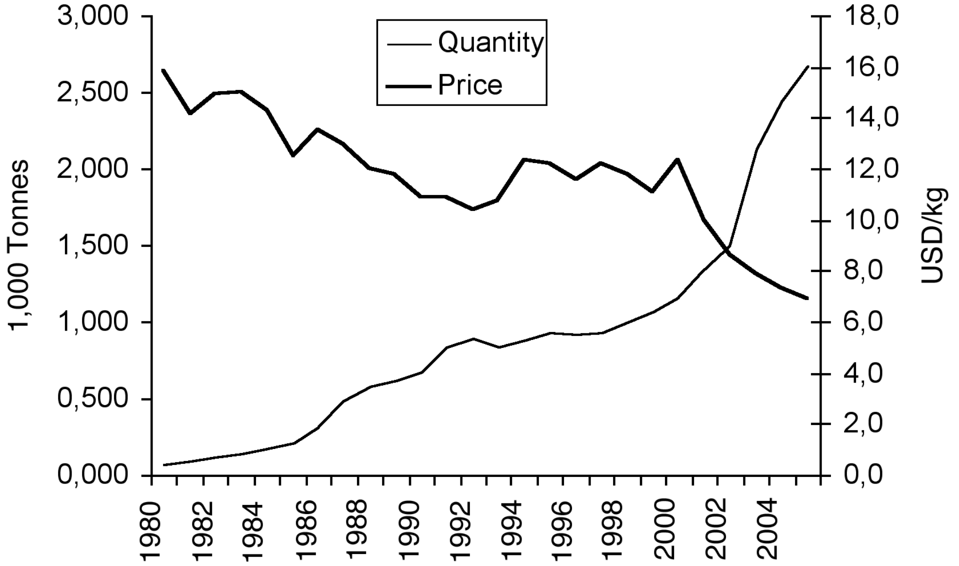

Figure 2. Global Shrimp Production and US Real Price, 1980–2005 (2005=1)
Sources: FAO (2008b); NMFS (2008).

While aquaculture has been a clear success when it comes to quantity produced, it has also raised some significant environmental concerns (Naylor *et al.* 2000). Aquaculture interacts with its surrounding environment, which is common with most other biological production practices. If one is careful, it is not difficult to be a sustainable aquaculture producer. However, there are a number of examples of unsustainable aquaculture practices. Hence, aquaculture has the potential to significantly impact the environment; more so the more intensive the production process. The same control that allowed productivity growth can also be used to control environmental impact. However, to use this control over the production process also in this respect may well be one if the industry's biggest challenges. Still, it is necessary if aquaculture is to become a significant source of sustainably produced food.

This article is organized as follows. In the next section, the development in agriculture is described briefly, and it is argued that this is a good point of reference for what will be further development of aquaculture. This is followed by a section discussing the importance of control over the production process for the development of aquaculture. Control over the production process leads to more intensive production and larger plants, as there are economies of scale. It also allows for the development of specialized providers of services to the industry, as well as innovations and productivity growth in the supply chain. Finally, the environmental challenges for the aquaculture industry are discussed briefly before some concluding remarks with respect to the future opportunities and challenges of the industry are offered.

Agriculture and Aquaculture

If one is to assess the development of aquaculture based on any existing industry, it must be agriculture; particularly chicken and pork production. These are two of the world's main sources of meat (the other two being lamb and beef). Many will argue that aquaculture is primarily knowledge about animal production applied to seafood. This was certainly the case for salmon in Norway, where initially the key knowledge providers came from the then Agricultural University of Norway (Gjedrem 2007).[1]

The origins of agriculture were the cultivation of different types of grain and domestication of livestock in the Fertile Crescent about ten thousand years ago (Cohen 1977). As time went by, the initially domesticated species were spread over larger areas and new species were domesticated in this process, as well as in other places where agriculture originated independently (Bellwood 2005). The spread of agricultural practices from a few key areas and significant trade has led most agricultural crops today to be introduced species. Over time, a number of innovations have made agriculture more intensive. These innovations include irrigation techniques, crop rotation, systematic breeding, introduction of new species, mechanization and better tools, and the use of fertilizer, allowing the farmer increased control over the production process. By becoming increasingly intensive, agriculture has enabled humanity to increase its global food-producing capacity tremendously. The numbers used to describe the results are often staggering. For instance, wheat yields in England took nearly 1,000 years to increase from 0.5 tonnes per hectare to 2 tonnes per hectare, but only 40 years to increase from 2 tonnes per hectare to 6 tonnes per hectare at the start of the 21st century (Hazel 2003). Similarly, in the USA the time it takes to produce a chicken has been reduced from about three months to six weeks over a fifty year time span. The innovation

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[1] In 2006 the university changed its name to the Norwegian University of Life Sciences.

rate and the increase in food production seem to be exponential, as the most significant changes have been in the twentieth century (Gardner 2002; Mundlak 2005).

The intensification of agriculture and its increased scale of operation have also allowed significant specialisation in the production process. Currently, one can observe not only specialized suppliers of tools and equipment, but also specialized feed producers, breeders, hatcheries, *etc.* Moreover, specialized industries that supply specialized inputs like pharmaceuticals and fertilizers have also developed. By focusing on specific processes, more innovation seems to take place and economies of scale can be exploited, further contributing to increased yields and lower costs. Furthermore, better and cheaper logistics and transportation have allowed the inputs, as well as the product, to be shipped over significant distances. This has increased market size for the farmers, and increased the supply of quality food to most parts of the world. Hence, the share of the world's population that has a concern with respect to how to find the next meal has been decreasing.

In figure 3, US prices of corn and wheat are shown for the period 1914-2007 (and the development is similar for many other crops, including soya). Two features are immediately apparent. First, the prices are highly cyclical, and one can clearly see the effect of the food shortage in the 1970s. Secondly, and more importantly, prices have a clear downward trend despite the significant cycles. In figure 4, the real price of live broilers is shown to provide an indication of development of the poultry industry. As one can see, the price has fallen even faster than for corn and wheat, and it is less cyclical. This indicates that feed producers for chicken can substitute between inputs in their feed and that productivity growth has been faster for chicken production than for corn and wheat production.

The downward trend in the prices for wheat, corn, broilers, and most other agricultural products is the result of all the productivity-enhancing innovations, and it

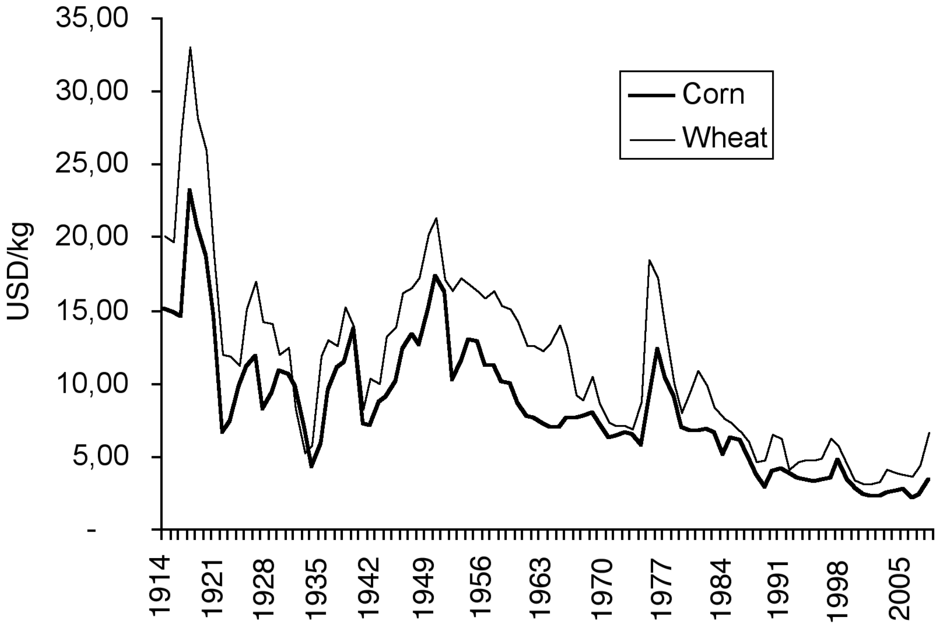

Figure 3. Real US Price for Corn and Wheat 1914–2007 (2007=1)
Source: USDA (2008).

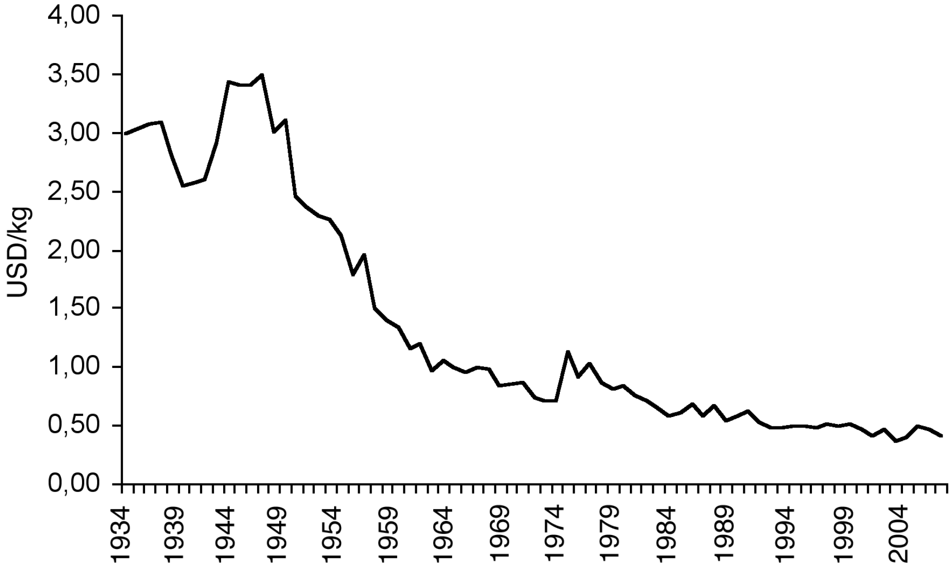

Figure 4. US Real Price for Live Broilers, 1934–2007 (2007=1)
Source: USDA (2008).

has contributed significantly to the food availability for a large number of people due to the decreased cost. As two of the three world's most important crops, the effect of lower corn and wheat prices is important in itself (FAO 2008a). Intensively produced broilers may be less important globally, but are still important to the food supply in most developed countries. The price trends shown here are also typical for most agricultural commodities that are traded in open markets. The productivity growth and intensification of agriculture has led the price of most important varieties to decline significantly in real terms. Gardner (2002) provides a good account for the USA, and Mundlak (2005) relates this to a number of other countries.

Agriculture is certainly not equally intensive everywhere, and hunting, gathering, or very extensive farming practices are still used as food producing technologies in many places worldwide. However, because such production techniques are not very efficient, the share they represent of the world's food supply is relatively less important. Moreover, there is a clear tendency that such practices are associated with societies where a very high share of the population is still farmers and are still very poor. The only clear exception to this rule seems to be organic farms targeting the high-end market of environmentally conscious consumers.

While agriculture has been very successful in increasing food production in much of the world, it has certainly had and still has its problems. Agriculture has a huge environmental impact as landscapes are transformed, something that still continues with a substantial deforestation. Erosion or overuse of the soil can make the land unproductive, and there are numerous examples indicating that agriculture is being conducted in an unsustainable manner. In relation to the Green Revolution, there has been substantial criticism in this respect (Evenson and Gollin 2003; Hazel 2003; Shiva 1992). These issues are a set of challenges that have to be mastered for agriculture to be sustainable, and although not always successful, the general experience of the previous millennia is positive.

However, many critics of the intensification of agriculture seem to overlook many of the positive effects. For instance, the doubling of the rice yields in Asia due to the Green Revolution has significantly reduced poverty, increased food availability, and reduced demand for new land and therefore deforestation (Hazel 2003). And although obesity is regarded as an increasing problem in the developed world, the improved availability of food is a main factor in the increased life expectancy in these countries. Furthermore, compared to food shortages and hunger, obesity is relatively minor and primarily an ethical issue.

Control over the Biological Production Process in Aquaculture

Aquaculture faces many of the same opportunities and challenges as agriculture has faced, and, in general, solved well. If aquaculture is to become a major supplier of food, it will have to exploit the technological opportunities in a similar fashion. Moreover, one can hope that aquaculture will be able to meet the environmental challenges, even though the evidence so far is mixed.

The key factor for the success of aquaculture as a major supplier of food is control over the production process. Cultivation of a new species typically begins by catching wild juveniles and raising them in a controlled environment. Whether that is a cage in a riverboat in the Mekong Delta, a pond in Bangladesh, a rope in France, or a pen in Norway does not matter much. However, as soon as the fish becomes more than a taker of household or farm disposables, it is obvious how different feeds and environments influence its growth. This starts the innovation process and systematic gathering of knowledge. However, as long as the farmer depends on wild juveniles, the scope for development in the farming process is limited.

Only when farmers close the production cycle and produce juveniles from a breeding stock kept in captivity, the control over the biological production process becomes sufficient for significant innovations. This is because it is at this stage that the production process lends itself to systematic knowledge gathering and scientific research at all levels. It is this systematic research that when cumulated provides the productivity improvements that allow a biological industry to become a significant food producer. Moreover, the possibility of systematic research also opens up the potential for specialization, as control allows one to take on a few issues at a time. Hence, some researchers can focus on creating the best feed, some on breeding, others on disease control, *etc.* As the new knowledge is used, control over the production process is increased, and the intensity of the production process increases.

The effect of productivity growth in aquaculture is significant. In figures 1 and 2 it is shown how the real price of salmon and shrimp declined as production increased. The continuing growth in production is profitable only if production costs are being reduced due to productivity growth. This can also be seen in figure 5 for salmon, the only species where cost data is available over time. In figure 5, the real Norwegian production cost is shown together with the export price. In 2007, the production cost as well as the export price is about one quarter of what they were in the mid-1980s. Hence, the reduction in production cost due to innovations and productivity growth has largely been passed on to the salmon consumers.[2]

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[2] It is also worthwhile to note that there are significant variations in the short-run relationship between cost and price, indicating cycles in profitability. This is further discussed in Andersen, Roll, and Tveterås (2008) and Oglend and Sikveland (2008).

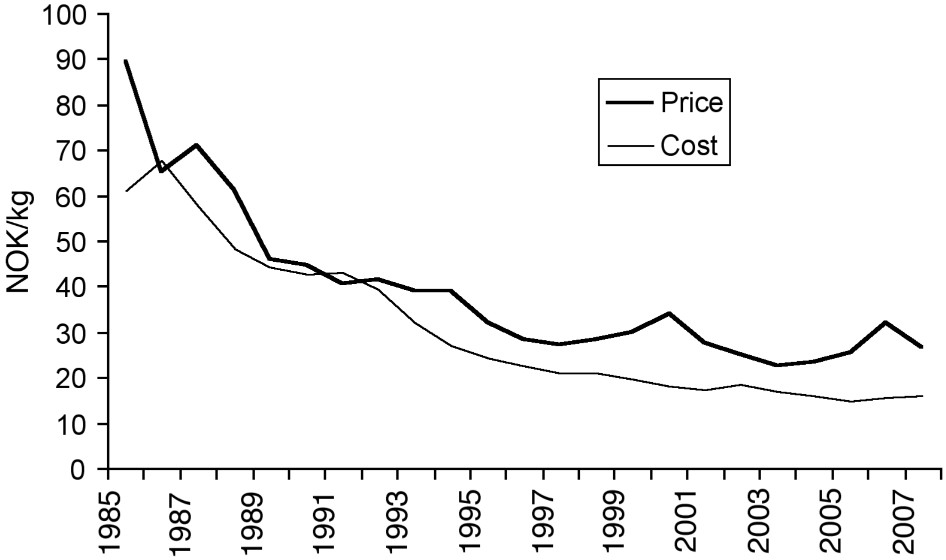

Figure 5. Real Norwegian Production Cost and Export Price for Salmon, NOK/kg, 1985–2007 (2006=1)

Source: Norwegian Directorate of Fisheries (2008); Norwegian Seafood Export Council (2008).

Intensity and Scale

Several criteria can be used to classify an aquaculture system (Bjørndal 1990). From an economic point of view the most significant criterion is intensity, where the most common categorization is the division into extensive, semi-intensive, or intensive forms of culture. Measures of intensity include stocking density, production by area, feeding regimes, and input costs, while the most interesting feature is the degree of control within the production process. Whether the farming process takes place in pens as for salmon, ponds for shrimp or tilapia, or land-based tanks as for turbot, the farmer in an intensive operation controls factors of production such as farm size, stocking, and feeding of fish. In contrast, traditional aquaculture varies between semi-intensive and extensive, and the farmer has significantly less control over the production process. Mussel farming is an example of an extensive method used around the globe, where the farmer primarily provides a rope or a stake for the mussel fry to fasten onto. Sometimes the ropes are culled, but otherwise the mussels are left to grow on their own. The small ponds used in Chinese aquaculture were traditionally operated on an extensive basis, as the farmer did little to control growth and biomass. While this system is still common, many farmers have become semi-intensive, as they actively feed their fish and maintain higher densities as well as adopt other production-enhancing technologies.[3]

Accordingly there is a strong relationship between control over the production process and intensity, as control over the production process is a requirement for a

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[3] An interesting way to measure the effect of the intensification even in traditional Chinese aquaculture is the split of the harvest value between the farmer and the fishers that are hired to harvest fish from the farm. Traditionally, this split was 50–50. During the last decades this has changed, and 75–25 to the farmers' advantage is increasingly common.

high-intensity operation. With a high intensity, a farmer will also be concerned about how to best exploit the advantages the control gives. For instance, the farmer will try to figure out the optimal plant size, how to best utilize capital equipment, *etc.* As much capital equipment requires a certain level of production to be reasonably utilized, this will often favour larger plants. For instance, a single automatic feeder can easily feed 500,000 fish. However, to avoid wasting feed, the feeder can only be used for a single pond or pen. Efficient utilization of the feeder then favours larger pens. In salmon farming increasing pen size has been the trend. In the early 1980s pens typically had a diameter of about five meters and were four meters deep. Today a typical new pen is about 50 meters in diameter and reaches 40 meters bellow the surface.[4] As more capital equipment is employed to improve the production process, such as light, oxygen supply, and tracking devices, scale becomes even more important, as capital equipment cannot be divided between different ponds or pens. To best utilize the methods associated with intensive farming and the capital equipment associated with it, a relatively large-scale operation is often necessary. Thus, it is often observed that high-intensity operations are larger and operate at a larger scale than more extensive operations.

While high-intensity and large-scale operations are important in achieving the most efficient production of seafood, the techniques can also be misused and lead to unsustainable practices. For instance, there exist a number of anecdotes relating to how some aquaculture producers “mine” their location. Under such conditions, one uses control over the production process to overstock the location with a very high density of fish. This may be profitable in the short run as one produces more, but may cause long-term or irreparable environmental damage to the location. If there are enough cheap locations available and local governance is poor, the farmer can find it profitable to move to a new location. Hence, such practices are primarily a governance problem. However, it is a challenge since cases it is often the smallest (and usually poorest) farmers that have the highest stocking density (Gordon *et al.* 2008).

When considering the merit of intensive production systems, it is important to note that the only way to increase production significantly in an extensive system is to increase the area used. Hence, as in agriculture, if one is to produce more of a species, one must either increase the area that is farmed or apply new, more intensive technology that increases the productivity of a given area.[5] It is not obvious what the best approach from an environmental perspective is if one is to increase food production, independent of whether the increase is from agriculture or aquaculture. Intensification leads to one set of environmental challenges and often higher discharges (Morrison Paul *et al.* 2002; Tveterås 2002), while increasing the area that is farmed changes land use and often leads to deforestation.

A relatively intensive production technology is necessary for aquaculture to become industrialised, allowing large-scale production to benefit from cost-saving economies of scale. It is therefore not surprising that for the species where one has most control over the production process, plant size tends to be largest. However, there are exceptions to this, like the highly intensive closed recirculation systems that are used in some plants to produce live or super fresh fish near large population centres in the USA and Europe.

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[4] The largest single cage to my knowledge has a diameter of 70 meters and is designed to hold one million smolts.

[5] Mundlak (2005) provides a good illustration for US agriculture where increased food production in the 19th century was due primarily to increased size of the area being farmed. In the 20th century, it is increasingly high intensity that leads to greater agricultural production.

Specialized Suppliers

While control over the production process is necessary for specialized research and development, the size of the industry is essential for utilization of specialized suppliers. Demand from a small industry for virtually any service is limited; while with a larger industry, different services are needed more frequently, thus increasing demand. Specialized services tend to have higher productivity and lower cost, and specialized services reduce production cost if the market is large enough for them to be provided (Porter 1990a).[6] For instance, a biologist will normally know more about the growth process of the fish than the farmer. However, a small farmer cannot cover the salary of a biologist and as such, will not utilize a biologist's services. On the other hand, in a region with many farms, the industry's combined demand for services from the biologist can make it worthwhile for a biologist to set up her service. Alternatively, if the aquaculture company becomes sufficiently large, the company can afford more specialized staff, as their services can be used in many production units. Few, if any, firms can aspire to have all specialized services inhouse, and while larger firms tend to have more staff with specialized skills, there is still a tendency that the larger an industry is, the more specialized services will be demanded, and a significant part will be supplied by independent firms.

Independent specialized suppliers do not only have specialized knowledge in their field. To remain competitive they will often also conduct research and development on their own in their specialized field, further contributing to the total research conducted in relation to an industry. Hence, the suppliers also contribute to control over the production process and innovation. This can be very important. For instance, in Norwegian salmon aquaculture technical progress at the farm level only explains about one-third of the reduction in production costs (Tveteras and Heshmati 2002). Decreases in input factor prices and improved input factor quality, or technological innovations among the suppliers of input factors, make up the remainder. There are also spectacular successes that are made possible because of the existence of specialized suppliers. Among the most important innovations in salmon aquaculture was the introduction of an oil vaccine in 1991. Industry sources indicate that this single innovation reduced production cost by 5–10% from one year to another. Similar developments can also be found for other species. For instance, in the 1990s, production of black tiger shrimp increased relative to white shrimp because of disease outbreaks for white shrimp. However, after more disease resistant varieties of white shrimp were developed, production of white shrimp has increased during the last decade.

The importance of research and development by suppliers also leads to continuous changes in the input mix. Guttormsen (2002) shows that over time the cost share of feed has increased significantly in salmon farming, indicating that the utilisation of other factors, like capital and labour, improved. This is despite the fact that the feed in itself has improved dramatically, and the feed conversion ratio has been reduced (Tveterås 2002). Porter (1990a,b) shows that industry clusters with specialised suppliers tend to be more competitive, as the cluster enables more specialization and more knowledge transfers. This is an argument that not only is industry size important, but proximity matters. This is true also in aquaculture, as shown by Tveteras (2002) and Tveteras and Battese (2006).

Given the total production of salmon and shrimp, it is no surprise that one can buy feed specially designed for them, but not for species with smaller production like cod or tuna. This is basically a function of industry size. Also, salmon and

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[6] This is one of the main elements in Porter's cluster theory.

shrimp farmers started by mixing their own feed. However, when the industry became sufficiently large, it became profitable and worthwhile for specialized feed producers. Thereafter, the feeding industry rapidly became a very good example of the innovative power of specialized producers. One produced better pellets. One introduced dried pellets, allowing a significant reduction in the dependence of fresh trash fish and cut-offs from local fish-processing plants as a source of feed. This also made local production independent of local availability of feed ingredients, as one could access the global meal and oil markets. The dried pellets also allowed the inception of a new industry of specialized suppliers; the producers of feeders and feed control systems, which further contributed to productivity growth.

Many of the innovations and knowledge derived from the first aquaculture species that developed into significant industries, such as salmon and shrimp, are applicable to other species with minor adjustments. Hence, more knowledge is available and as such, the creation of aquaculture industries based on new species has been made easier by the development of the industry so far. However, the specific adjustments necessary for each species remain, and without specialized suppliers this development progresses slowly, if at all. This still makes the early phase difficult for most new species. This is even more so in developing countries where poor infrastructure makes it more difficult to establish specialized services, and it is particularly true for the two most important input factors, juveniles and feed.

If juveniles are harvested from wild stocks, no breeding is possible. If replenishment of a stock is primarily provided by spawning individuals at the farm, no breeding can take place. As these are the most common restocking techniques for new species and in poor developing countries, a major source for productivity improvement cannot be tapped. Similar to what was done at agricultural research stations and universities, governments in some developing countries, like China, seek to address this shortcoming by public funding. For some species, particularly tilapia, international organizations, such as Worldfish, also attempt to address the issue (Pemsl *et al.* 2008). These efforts are also very important. For instance, improved strains of white shrimp have significantly reduced disease problems. Currently, salmon on Norwegian farms need significantly less feed than their wild cousins to reach the same weight (Thodesen *et al.* 1999). This is also true for improved stains of tilapia (Dey *et al.* 2000).

For producers with limited access to credit, feed development is also slow. Poot-López and Gasca-Leyva (2006) provide an interesting example from tilapia farming in Mexico, where production, to a large extent, is determined by the farmers' availability of cash to buy feed. In extensive farming, biological household and farm leftovers are used as fish feed, and in a number of places trash fish is an important feed source. However, it is only for formula-based feed that one can conduct research with respect to how the feed meets dietary needs and in a systematic way influences the growth rate of the fish. As such, a low feed cost share is generally not a good sign, rather the opposite. It is an indication of an operation with little feed supply development and limited control over the production process. For salmon, the cost share of feed has increased from about 25% to over 50% during the last 25 years as all other factors are utilized more efficiently (Guttormsen 2002). For the best chicken producers, the cost share of feed is even higher.

Control of the Production Process Increases Control in the Supply Chain

For the competitiveness of a product, it is not only the innovations directly related to the production process that are important. Given that one has sufficient control over the biological production process, it is equally important how the production process is organized for the industry to be successful.[7] In fact, a successful aquaculture industry also requires a well functioning supply chain from the producer to the consumer. Market price is often the most important argument with respect to which product in a group of products a retailer will stock, and total production cost will be the main factor explaining which aquaculture products will be produced. Total production cost is defined as the total cost of bringing the product to the consumer, including transportation and processing costs. Hence, it is the whole process of bringing the product to the consumer that is of interest, and innovations in logistics are equally important as innovations in the production process for the industry to be competitive.

What products and species will be produced largely depends on which species have the lowest production costs. Moreover, choice of production location depends on which area offers the most competitive advantages in terms of access to suitable land/sea localities, good market access, favourable regulations, *etc*., and long distance to the market and high transportation costs can at least partly be compensated by lower production costs for distant producers. The international trade in tilapia offers an interesting example. The USA is the main import market. However, imports of fresh fillets are primarily from Latin America, while frozen imports are from Asia (Norman-Lopez and Asche 2008). The reason for this difference is that for frozen fish, transportation costs are not very significant, making lower production cost a definite advantage for Asian producers. For fresh fillets on the other hand, transportation costs are much higher and distance matters, giving Latin American countries the competitive advantage.

A particularly interesting example of how the aquaculture industry can interact with the supply chain and the market is provided by Chilean salmon exports to the USA. In figure 6, US imports of Chilean salmon are shown by product form/species. As one can see, exports started with fresh coho, a species caught in substantial quantities by US fishermen. However, it was quickly discovered that Atlantic salmon was the preferred species along the Eastern Seaboard, where the main markets were located. Hence, from 1991 whole fresh Atlantic salmon took over as the leading species and product form. Fresh fillets were introduced in the early 1990s and quickly became a success, and by 1997 they had taken over as the leading product form by product weight. At the same time, exports of whole fresh salmon started to decline. As the market for salmon became more sophisticated, with increased processing, ready meals, and discount sales, Chile also started exporting substantial quantities of frozen fillets.

Better control over the supply chain also allows more diversification, product development, and market orientation. Aquaculture products now show up in a number of settings where seafood normally has not been found. This is true for high-quality cuts, but even more for how the scraps and other parts are used. Again, the process resembles what one has observed in the meat industry in developed markets, as described by Horowitz (2006) for the USA. As such, it is no accident that salmon sausage is a recent success story in several markets.

Aquaculture and the Environment

While the development of new technology has significantly increased the production potential of aquaculture, increased production has led to questions with respect to environmental impact and, in some cases the sustainability of aquaculture. This is

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[7] Productivity growth in the supply chain has received significantly less attention than productivity growth in the production process. Asche, Roll, and Tveteras (2007) provide a discussion for salmon, and Guillotreau, le Grel, and Simoni (2005) and Asche and Tveterås (2008) provide price transmission studies.

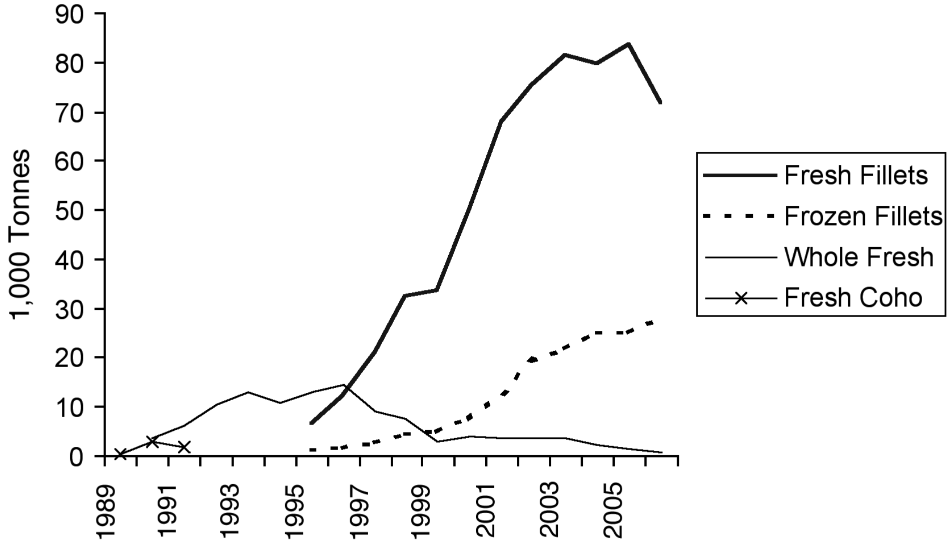

Figure 6. US Imports of Chilean Salmon, 1989–2006
Source: NMFS (2008).

certainly an issue, as aquaculture like any other biological production process, interacts with the surrounding environment.[8] Moreover, for some species there is a global supply network, as globally traded fish meal and fish oil is used in the feed. The environmental challenges appear as two different main issues; local environmental carrying capacity and limited availability of food (the fish meal trap).

Local Environmental Issues

Whenever the environment and a production process interact, there is potential for damaging the surrounding environment. The potential damages include destruction of natural habitat and pollution that influences habitat and wildlife around the site. As the two most successful aquaculture species, salmon and shrimp are also the species that have received the most attention with respect to environmental impact (Naylor *et al.* 2000). For salmon farming the main issues are pollution from organic waste and the interaction between wild and farmed fish. Farmed salmon may transmit diseases and parasites to wild salmon, and sea lice typically found on wild salmon has been associated with escaped farmed salmon. Farmed salmon may also attempt to spawn in rivers, potentially affecting the genetic pool. Shrimp farming has received even more negative publicity than salmon farming in relation to detrimental environmental effects, such as destruction of mangroves, salinization of agricultural areas, eutrophication, and disruptive socio-economic impacts.

When discussing environmental issues associated with intensive salmon and shrimp farming, one must take into account that this is relatively new technology. As with all new technology, there may be unexpected side effects and a time lag from

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[8] Holmer *et al.* (2008) provide a number of examples of environmental challenges in aquaculture.

when an issue arises until it can be addressed. First, the causes and impacts must be properly identified. Second, the solution to the problems will require modifications of existing technology or maybe entirely new technology. In both cases, pollution reduction implies some form of induced innovation. In this relation, Tveterås (2002) argues that industry growth has a positive effect on pollution, in line with the Environmental Kuznets Curve (EKC). The EKC hypothesis refers to an empirical observation that pollution tends to increase with economic growth up to a certain point, after which growth will reduce pollution. This gives the pollution profile over time an inverted U shape. Use of antibiotics in Norwegian aquaculture is a good example, as can be seen in figure 7. Moreover, the greater the aquaculture production and the more intensive the process is at any site, the greater the potential for environmental damage. However, the greater degree of control over the intensive aquaculture production process makes it easier to address these issues.

There are two main reasons the industry needs to address environmental effects: (*i*) they reduce productivity and profits, and/or (*ii*) government regulations force the industry to do so. Industry size contributes to the availability of environmental impact-reducing technologies because a large industry enables more investment, and thereby provides more incentive for development of abatement technologies. Detrimental environmental effects of aquaculture not accounted for in market prices are negative externalities. Asche, Guttormsen, and Tveterås (1999) argue that internalization of the externalities explains why some of the major environmental issues have been resolved in aquaculture. The arguments go as follows: Production cost and productivity in aquaculture depends on an environment where farmed fish is raised. Fish farms with environmental practices that harm the local environment will experience negative feedback effects from poorer growing conditions, reducing on-farm productivity. The result is reduced biomass growth due to poor fish health, and, in the worst case, disease outbreaks that wipe out entire on-farm stocks. Hence, a farmer is concerned with cultivating management practices that avoid such negative repercussions on productivity.

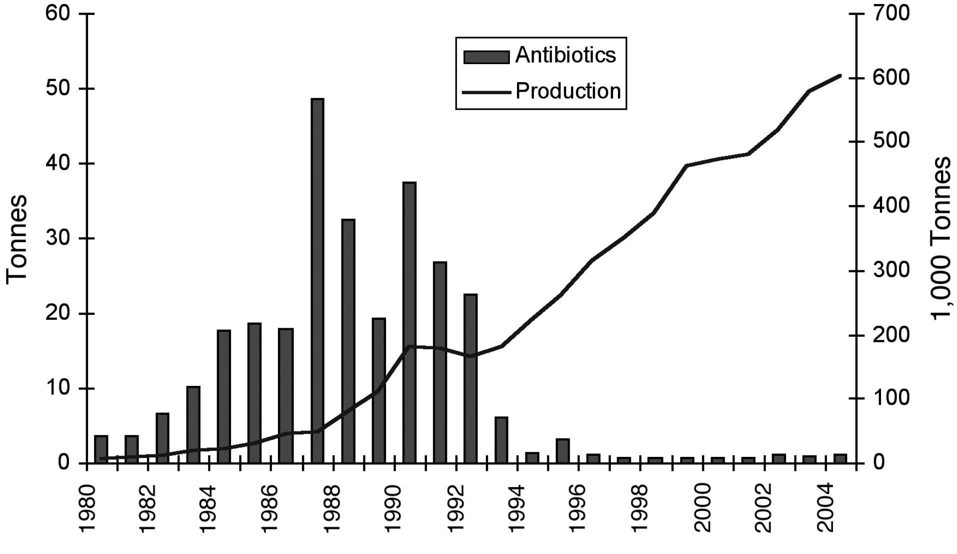

Figure 7. Norwegian Salmon Production and Antibiotics Use in Norwegian Aquaculture

Source: Norwegian Directorate of Fisheries (2008).

If there is no negative feedback on expected profitability, however, it is unlikely that the industry will internalize detrimental environmental effects. In this case the government has to regulate the industry if the effects are to be avoided. The rapid growth of global aquaculture represents an environmental challenge for authorities. First, knowledge about the environmental effects of aquaculture has been limited, or at worst, lacking. This has called for extensive research to identify causes and effects. Second, in many places local governments do not have the resources to implement and enforce regulations. On the one hand, it is desirable that regulations are efficient in addressing the externalities. On the other, they may allow the aquaculture industry to be economically sustainable, if that combination is possible. It is also of interest to note that often there are scale economies in adapting environmentally beneficial technologies and sustainable practices as well as regulations. Again, this highlights that intensive large-scale operations face increased environmental challenges, but also have greater capacity to address them.

The Fish Meal Trap

The 'fish meal trap' is a hypothesis that claims that aquaculture is environmentally degrading because increased demand for feed leads to increased fishing effort and thereby threatens the viability of wild fish stocks (Naylor *et al*. 2000). Moreover, it follows from this hypothesis that the availability of marine feed will put a limit on how much the aquaculture sector can produce, given that the availability of wild fish is limited. While the fish meal trap is mentioned in relation to aquaculture in general, it is clear that it is a serious issue only in some forms of finfish farming, and it does not apply to farming of seaweeds and shellfish. Furthermore, it will only apply to species fed with feed using primarily marine inputs. This is a substantial part of the sector, as this is the case not only for carnivorous species, like salmon and sea bass, but also for omni- or herbivorous species because the use of feed increases the growth rate. There are, however, some conditions that must be fulfilled for the fish meal trap to occur (Asche and Tveterås 2004; Kristoffersson and Anderson 2006).

Whether the fish meal trap represents an environmental problem or not can be decomposed into two key issues—one pertaining to the regulation of capture fisheries and one pertaining to the market for protein meals. To what extent increasing demand for fish meal increases fishing effort is related to the management regime in operation for the fishery in question. With a working management system, increased demand for the species cannot threaten the fish stock (Munro and Scott 1985). Hence, whether growth in aquaculture production can lead to unsustainable capture fisheries is primarily a fisheries management problem. However, as the track record of many fisheries management systems is not too good, this can be a real problem. Still, for increased demand from aquaculture to have an impact, it is necessary that aquaculture growth increases total demand for fish meal.

Traditionally, there has been a strong link between the market for fish meal and the market for other vegetable meals, as different users have substituted between the different types of meals depending on price development. This has kept price development closely aligned (Vukina and Anderson 1993; Asche and Tveterås 2004). This also implies that fish meal has not been demanded for its unique properties. Fish meal production has not increased during the last 30 years, the period in which industrialised aquaculture has expanded. There is accordingly little evidence indicating that the fish meal trap has been an issue.

In 1999 the stable price relationship between fish meal and vegetable meals ended (Kristoffersson and Anderson 2006), and from early-2005 to mid-2006 fish meal prices more than doubled to a record high level. This indicates that fish meal is now in demand due to its unique attributes. Still, it seems like growth in aquaculture production is fairly independent of the cycles in fish meal prices and of the availability of fish meal. In figure 8 the global production of fish meal and aquaculture production is shown. As one can see, there is a very strong growth in total aquaculture production, while the supply of fish meal is relatively stable. Hence, the variation in fish meal price does not seem to have a strong impact on aquaculture production, and most aquaculture producers do not seem to require fish meal in large quantities. Accordingly, for most aquaculture species, fish meal does not seem to be an essential feed ingredient, and even when fish meal is demanded primarily for its unique attributes, aquaculture does not seem to be the main force in the increased demand. However, to the extent that there are species that require sufficient quantities of fish meal, producers of these species will find that feed costs will become more volatile, and if the price continues to increase, it may be a problem for the profitability of the operation.[9]

Since increased productivity is the main engine of growth in aquaculture, increased fish meal prices would prevent further growth for species that are too dependent on marine sources for food. The commercial breakthrough of cod aquaculture, for example, will probably be constrained if fish meal prices remain at high levels. Hence, scarcity may constrain growth of high-priced carnivore aquaculture species, particularly in the short run when feed technologies cannot be changed to include less fish meal. However, most aquaculture species are herbivores and even salmon are becoming semi-vegetarian. So, in terms of volume, fish meal demand from aquaculture should have a limited impact on the fish stocks used.

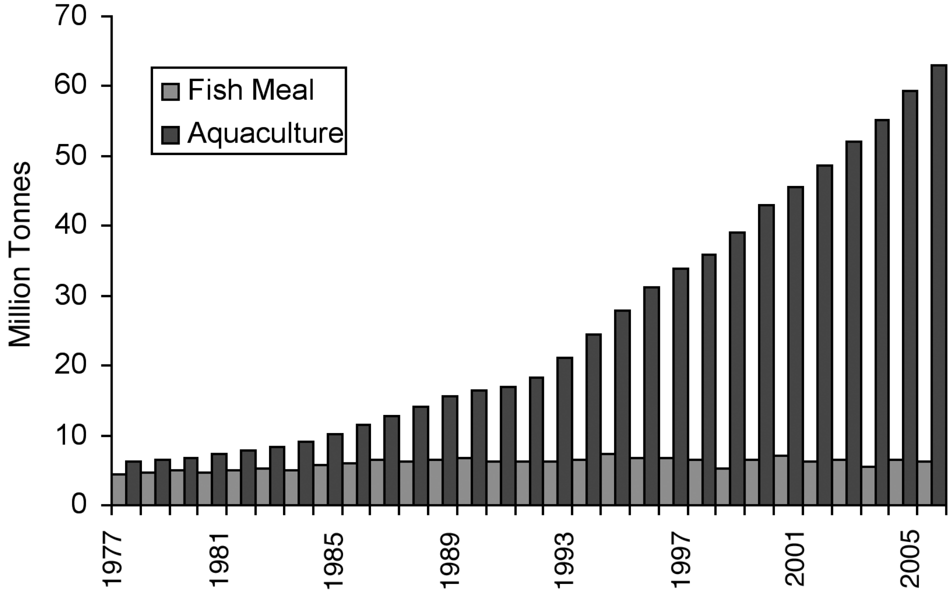

Figure 8. Global Annual Aquaculture and Fish Meal Production, 1980–2005
Source: FAO (2008).

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[9] While aquaculture expansion may have influenced recent price development, the main cause of the dramatic price increase seems to be the economic growth in China. The Chinese income growth has led to an increased demand for animal proteins, and in China fish meal is widely used in animal feeds such as for poultry, as well as for aquaculture.

Aquaculture and Sustainability

There are a number of examples of poor environmental practices in relation to aquaculture (as in agriculture). However, that does not make the production method inherently unsustainable. There are also a number of examples of sustainable aquaculture. Still, intensive and particularly large-scale intensive aquaculture has greater potential for detrimental environmental effects than other technologies. The higher degree of control over the production process does, on the other hand, give these farmers a better opportunity to also control the negative effects of their production.[10] As such, there is no doubt that aquaculture can be carried out in a sustainable manner, independent of the level of intensity. The real issue regarding aquaculture and sustainability is whether farmers chose to use sustainable practises. This will primarily be an issue of local regulations and governance, but may also be influenced by consumer initiatives and ecolabels.

Farmed Fish and Human Health

Generally speaking, eating fish is regarded as healthy, and the positive impact is also well documented (Mozaffarian and Rimm 2006). Seafood, particularly oily fish, has been shown to have positive effects on reducing cardiovascular and neurological disease in adults and on early neurodevelopment. However, seafood can contain contaminants like mercury and PCBs that increase the risk of cancer, and such information may reduce the likelihood of consumer purchase. This has led several researchers and environmental organizations to question whether the knowledge that fish is healthy is true also for farmed fish. However, while the information is contradictory, medical researchers seem to agree that the positive health effects are of a higher magnitude than the negative. For instance, Mozaffarian and Rimm (2006, p. 1985) state: "…levels of PCBs and dioxins in fish are low, similar to those in several other foods, and the magnitudes of risks in adults are greatly exceeded by benefits of fish intake and should have little impact on individual decisions regarding fish consumption." Hence, it is likely that consumption of seafood will continue to be associated with positive health effects, and influence demand positively. Different composition of feed recipes and increasing reliability on vegetable inputs do not change this significantly. For herbivore and omnivore species, the basic diet is not that much different. Even for carnivorous species like salmon, this is to a large extent true when compared to their wild cousins, as even diets with little fish meal and fish oil still maintain Omega 3 levels and sensoric quality.[11] As the knowledge about the fish's nutritional requirements improve, this problem may disappear.

Concluding Remarks

Extensive aquaculture is a food-producing technology that can be traced back thousands of years. However, for most of those years aquaculture's importance as a provider of food was limited. This has changed significantly since the 1970s with the introduction of semi-intensive and intensive farming practices, and with produc-

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[10] The most intensive operations, closed cycle systems where all emissions are cleaned, may be the most environmentally friendly systems. Proponents of such systems claim that clean water is the only emission.

[11] Fish produce a significant share of Omega 3s themselves, almost independently of diet. However, farmed fish fed feed with high marine content can have significantly higher levels of Omega 3 then their wild cousins.

ers who more actively influence the growing conditions of the fish with feeding, breeding, *etc*. Control over the production process has allowed a number of productivity-enhancing innovations to take place. These led to the development of semi-intensive and intensive production practices. A significant increase in productivity has reduced production costs substantially in intensive and semi-intensive aquaculture production. This provides strong incentives for producers to increase production, and for new producers to enter the industry. Substantial increases in the production of species, such as salmon and shrimp, tilapia, pangasius, sea bass, *etc*., have led to large reductions in price, making them more affordable for consumers and more competitive relatively to other food products.

Control of the aquaculture production process makes it similar to any other food growing industries in many ways. Accordingly, growth in other industries should hold a number of lessons and perspectives for the future growth of aquaculture. Although it is not perceived as a very dynamic industry in many parts of the world today, agriculture is the industry that is closest to aquaculture. By becoming increasingly intensive, agriculture has enabled humanity to increase the global food producing capacity tremendously. Certainly agriculture is not equally intensive everywhere, and hunting, gathering, or very extensive farming practices are still used as food producing technologies many places worldwide. However, because such production techniques are not very efficient, the share of the world's food supply they represent is relatively less important.

Agriculture certainly did and still does have problems. It has a huge environmental impact as landscapes are transformed, something that still continues with a substantial deforestation. Erosion or overuse of the soil can make the land unproductive, and there are numerous examples indicating that agriculture is conducted in an unsustainable manner. These issues are a set of challenges that have to be mastered for agriculture to be sustainable, and although not always successful, the general experience of the previous millennia is positive. Aquaculture faces many of the same opportunities and challenges as agriculture has faced, and, in general, solved well. With rapidly increasing control over the aquaculture production process, one can already see this challenge is being (at least partially) met in high growth industries like salmon and shrimp. However, it is likely that there will be a number of examples of poor environmental practices associated with aquaculture, as some producers will not comply with industry standards.

There is little doubt that aquaculture production will continue to grow substantially. As shown by Delgado *et al*. (2003), demand for seafood will grow because of increased economic growth and increased global population. This provides a positive environment for growth, provided that aquaculture products are competitive. It is clear that lower production costs due to productivity growth are the main engine for growth in aquaculture production. Although already a success story and an important seafood source, aquaculture is still in many ways in its infancy. For many species the production cycle is not closed; *i.e*., there is still dependency on the harvest of wild fingerlings rather than producing them from a domesticated stock. Hence, there is substantial potential for further productivity growth and for aquaculture production to become less costly. While there has been significant technological progress in aquaculture since the 1970s, when compared to agriculture and other industries, there is clearly a long way to go. There are too few dedicated systematic scientific researchers, specialized suppliers, species where one conducts systematic breeding, and no futures markets, *etc*. Hence, while there has been significant progress during the previous decades, there is still a long way to go until we are truly farming the sea. With the significant quantities of food that aquaculture is already providing, the potential for the future is tremendous. Moreover, while there are environmental challenges, increased food production from the sea will lead to a reduction in deforestation and pressure on terrestrial land to produce more food. It is accordingly far from clear, even with the aquaculture technologies used today, that the net environmental effect is negative.

References

Andersen, T., K.H. Roll, and S. Tveterås. 2008. The Price Responsiveness of Salmon Supply in the Short and Long Run. *Marine Resource Economics* 23(4):425–37.

Anderson, J.L. 2002. Aquaculture and the Future. *Marine Resource Economics* 17(2):133–52.

Asche, F., A.G. Guttormsen, and R. Tveteras. 1999. Environmental Problems, Productivity and Innovations in Norwegian Salmon Aquaculture. *Aquacultural Economics and Management* 3(March):19–30.

___. 2008. Aquacutlure: Opportunities and Challenges: Special Issue Introduction. *Marine Resource Economics* 23(4):395–400.

Asche, F., K.H. Roll, and R. Tveteras. 2007. Productivity Growth in the Supply Chain—Another Source of Competitiveness for Aquaculture. *Marine Resource Economics* 22:329–34.

Asche, F., and S. Tveterås. 2004. On the Relationship between Aquaculture and Reduction Fisheries. *Journal of Agricultural Economics* 55(2):245–65.

___. 2008. International Fish Trade and Exchange Rates: An Application to the Trade with Salmon and Fish Meal. *Applied Economics* 40:1745–55.

Bellwood, P. 2005. *First Farmers—The Origin of Agricultural Societies*. Oxford: Blackwell.

Bjørndal, T. 1990. *The Economics of Salmon Aquaculture*. Oxford: Blackwell.

Cohen, M.N. 1977. *The Food Crises in Prehistory—Overpopulation and the Origin of Agriculture*. New Haven, CT: Perseus Publishing.

Delgado, C.L., N. Wada, M.W. Rosengrant, S. Meijer, and M. Ahmed. 2003. *Fish to 2020: Supply and Demand in Changing Global Markets*. Washington, DC: IFPRI.

Dey, M.M., A.E. Eknath, L. Sifa, M.G. Hussain, T.M. Thien, N.V. Hao, S. Aypa, and N. Pongthana. 2000. Performance and Nature of Genetically Improved Farmed Tilapia: A Bioeconomic Analysis. *Aquaculture Economics and Management* 4(1&2):83–106.

Evenson, R.E., and D. Gollin. 2003. Assessing the Impact of the Green Revolution, 1960 to 2000. *Science* 300:758–62.

FAO. 2006. *The State of World Fisheries and Aquaculture*. Rome: FAO.

___. 2008a. *FAO Food Outlook: Global market Analysis*. Rome: FAO.

___. 2008b. *Fishstat Plus Database*. Rome: FAO.

Gardner, B.L. 2002. *American Agriculture in the Twentieth Century*. Cambridge, MA: Harvard University Press.

Gjedrem, T. 2007. *AKVAFORSK i Nasjonal og Internasjonal Akvakultur* (in Norwegian: *AKVAFORSK in Domestic and International Aquaculture*). Ås, Norway: Institutt for Akvakulturforskning.

Gordon, D.V., T. Bjørndal, M. Dey, and R.K. Talukder. 2008. An Intra-farm Study of Production Factors and Productivity for Shrimp Farms in Bangladesh: An Index Approach. *Marine Resource Economics* 23(4):411–24.

Guillotreau, P., L. le Grel, and M. Simioni. 2005. Price-Cost Margins and Structural Change: Sub-Contracting within the Salmon Marketing Chain. *Review of Development Economics* 9:581–97.

Guttormsen, A.G. 2002. Input Factor Substitutability in Salmon Aquaculture. *Marine Resource Economics* 17(2):91–102.

Hazel, P.B.R. 2003. Green Revolution. *Oxford Encyclopedia of Economic History*, J. Mokyr, ed. Oxford: Oxford University Press.

Holmer, M., K. Black, C. M. Duarte, N. Marba, and I. Karakassis. 2008. *Aquaculture in the Ecosystem*. Berlin: Springer.

Horowitz, R. 2006. *Putting Meat on the American Table: Taste, Technology, Transformation*. Baltimore, MD: John Hopkins University Press.

Kristofersson, D., and J.L. Anderson. 2006. Is there a Relationship between Fisheries and Farming? Interdependence of Fisheries, Animal Production and Aquaculture. *Marine Policy* 30(6):721–25.

Morrison Paul, C.J., V.E. Ball, R.G. Felthoven, A. Grube, and R.F. Nehring. 2002. Effective Costs and Chemical Use in United States Agricultural Production: Using the Environment as a "Free" Input. *American Journal of Agricultural Economics* 84(4):902–15.

Mozaffarian, D., and E.B. Rimm. 2006. Fish Intake, Contaminants, and Human Health: Evaluating the Risks and the Benefits. *Journal of the American Medical Association* 296(15):1885–99.

Mundlak, Y. 2005. Economic Growth: Lessons from Two Centuries of American Agriculture. *Journal of Economic Literature* 43(Dec.):989–1024.

Munro, G.R., and A.D. Scott. 1985. The Economics of Fisheries Management. *Handbook of Natural Resource and Energy Economics*, A.V. Kneese and J.L. Sweeny, eds. Amsterdam: North Holland.

National Marine Fisheries Service (NMFS). 2008. www.nmfs.gov

Naylor, R.L., R.J. Goldburg, J. Primavera, N. Kautsky, M. Beveridge, J. Clay, C. Folke, and J. Lubchenco. 2000. Effects of Aquaculture on World Fish Supplies. *Nature* 405(29):1017–24.

Norman-López, A., and F. Asche. 2008. Competition between Imported Tilapia and US Catfish in the US Market. *Marine Resource Economics* 23(2):99–214.

Norwegian Directorate of Fisheries. 2008. www.fiskeridirektoratet.no

Norwegian Seafood Export Council. 2008. www.seafood.no

Oglend, A., and M. Sikveland. 2008. The Behaviour of Salmon Price Volatility. *Marine Resource Economics* 23(4):487–506.

Pemsl, D.E., O.L. Chen, S. Tongruksawatta, Y. Garcia, E. Vera-Cruz, T. Abella, and H. Waibel. 2008. Adoption and Farm-Level Impact of Genetically Improved Farmed Tilapia (GIFT) in the Phillippines. Paper presented at IIFET 08, Nha Trang, Vietnam.

Poot-López, G.R., and E. Gasca-Leyva. 2005. Bioeconomic Evaluation of Substitution of Balanced Feed with Chaya (*Cnidoscolus chayamansa*) Leaves in Tilapia Production. Paper presented at The Economics of Aquaculture with Respect to Fisheries, December 9-10, Civitavecchia, Italy.

Porter, M.E. 1990a. *The Competitive Advantage of Nations*. London: MacMillan.

___. 1990b. Location, Competition, and Economics Development Devlopment: Local Clusters in a Global Economy. *Economic Development Quarterly* 14:15–34.

Shiva, V. 1992. *The Violenze of the Green Revolution: Ecological Degradation and Political Conflict in Punjab*. New Dehli: Zed Press.

Thodesen, J., B. Grisdale-Helland, S.J. Helland, and B. Gjerde. 1999. Feed Intake, Growth and Feed Utilization of Offspring from Wild and Selected Atlantic Salmon *Salmo salar*. *Aquaculture* 180:237–46.

Tveteras, R. 2002. Industrial Agglomeration and Production Costs in Norwegian Aquaculture. *Marine Resource Economics* 17(1):1–22.

Tveteras, R., and G.M. Battese. 2006. Agglomeration Externalities, Productivity and Technical Inefficiency. *Journal of Regional Science* 46:605–25.

Tveteras, R., and A. Heshmati. 2002. Patterns of Productivity Growth in the Norwegian Salmon Farming Industry. *International Review of Economics and Business* 49(3):367–93.

Tveterås, S. 2002. Norwegian Salmon Aquaculture and Sustainability: The Relationship Between Environmental Quality and Industry Growth. *Marine Resource Economics* 17(2):121–32.

United States Department of Agriculture (USDA). 2008. www.usda.gov

Vukina, T., and J.L. Anderson. 1993. A State-Space Forecasting Approach to Optimal Intertemporal Cross-Hedging. *American Journal of Agricultural Economics* 75:416–24.