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FORESIGHT PROJECT ON GLOBAL FOOD AND FARMING FUTURES

The application of science and technology development in shaping current and future aquaculture production systems

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SUMMARY

Aquaculture development over the past 50 years has been facilitated largely by the application of science and the introduction of new technologies. Although aquaculture is a very diverse sector in products, production systems and business structures, almost every activity has benefited from scientific advances. However, the impact of technological progress is most clearly seen where there has also been substantial industrial consolidation. This has provided greater capital resources for investment and a more attractive market for suppliers of innovations to target. It has also encouraged consolidation of research capacity and stronger articulation between private and publicly funded research efforts. Further development along current trajectories is possible through advances in genomics, information technology, materials science and other areas. However, there may also be substantial disruptions if, for instance, energy becomes much more expensive, or large mono-cultures are impacted by climate change. Substantial change could also be driven by policies that aim at bringing realistic external costs of environmental services into company accounts. Research into more resilient aquaculture systems that comply more with ecological than financial accounting principles is under way, but will require substantial development to meet the challenges of rising food needs and social aspirations.

INTRODUCTION

Aquaculture production, excluding aquatic plants, has risen from about 600 000 tonnes (t) in 1950 to 52·5 million t in 2008, accounting for *c*. 0·5 of fisheries product for human consumption (FAO 2010). Most of this increase has been achieved through the development of new farming practices and the expansion of culture volume (and area). It is a diverse sector encompassing subsistence-level smallholder ponds to billion-dollar international companies (Lazard *et al*. 2010) and over 300 species of fish, crustacean, mollusc or other aquatic animal (FAO 2010). The application of science and technology has enabled much of the growth in production and which also plays an important role in shaping the structure and economics of the sector.

Taking a reductionist approach, the principal drivers for commercial aquaculture are on one hand the desire for profit and on the other the need to compete effectively in the marketplace. The application of science and technology in aquaculture is therefore a reflection of companies seeking ways to make more profitable use of available natural and human resources to meet market demands. The actual aquaculture systems employed, while not perfect, represent an optimization of technology, resources and labour as they exist in a particular geo-social-economic environment to meet those ends, although increasingly oriented to global markets.

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While the area under aquatic cultivation has expanded substantially over the past 50 years, most of the increase in aquaculture production has been achieved (or enabled) through productivity growth (Asche *et al*. 2007). Scientific understanding has given rise to new management practices and in many cases the introduction of new technologies that have increased production levels when measured in terms of output per unit of land, water or labour employed. This intensification has also reduced unit production costs, making products more competitive on the market (e.g. Barazi-Yeroulanos 2010). The development of new technologies and their uptake for competitive advantage is most evident in the industrial aquaculture sector, of which salmon is at the forefront. While this species represents just 0·03 of global aquaculture production by volume and 0·08 by value (2008 data, excluding aquatic plants – FAO 2010), its patterns of development and technology use can also be seen in other industrializing aquaculture sectors (mainly in the West, but increasingly in other regions supplying Western markets).

The present paper focuses particularly on the relationship between technology development and adoption in aquaculture, and the trend of privatization and consolidation of global value chains in fisheries products (Swinnen & Maertens 2007). In addition to encouraging more intensive and larger-scale production, they also drive higher product safety, quality and often environmental and welfare standards, all of which are enabled through advances in science and technology. With respect to aquaculture production, the main areas of scientific and technical development can be grouped into reproductive control, nutrition, health, containment systems and environment. Closely allied to these have been advances in the management of production units, processing and packaging, market chain logistics and sectoral planning and administration.

STATE OF THE ART

Reproductive control and seed supply

Gaining control over the full lifecycle of aquaculture species has played a major role in facilitating the expansion of production. Hatcheries allow juvenile (or seed stock) to be produced to meet the requirements of grow out for market. Manipulations at this stage allow seed to be produced outside of the normal reproductive season for the species concerned, allow a single sex to be produced, or make possible selective breeding programmes for longer-term improvement in heritable traits such as growth rate, disease resistance or food conversion efficiency (Bromage 2001). In general, marine species have proved more challenging than freshwater species, mostly due to smaller egg sizes and more complex larval development patterns. One of the most notable aquaculture industries to emerge from the development of marine hatchery technology was Mediterranean sea bass and sea bream. Research during the 1970s paved the way for rapid commercial development during the 1980s to an industry worth over US$1 billion at first sale value in 2008 (FAO 2010).

The significance of manipulations at the hatchery stage is perhaps best illustrated by the rainbow trout industry. All-female (often sterile) juveniles can be produced almost year-round for faster growth and no loss of condition due to early maturity. Such advances raised the average production in Scotland from 23 t per farm in 1979 to 174 t per farm in 2008 and production per person from 10·6 to 54·4 t/yr (Munro *et al*. 1979; Marine Scotland Science 2009). Over the same period, the number of farms was reduced by 20% while production rose by 600%, illustrating how increased output is being achieved through productivity improvements rather than growth in the number of farms.

The impact of selective breeding can be seen in the salmon industry, where the production cycle has been reduced from 3–4 years to 2–3 years and average weight at harvest has risen from 2·7 kg in 1985 to 4·5 kg in 2006 (SOAFD 1991; Marine Scotland Science 2009). Specialist salmon-breeding companies have emerged using genotyping and quantitative trait loci (QTL) to assist selection. This has led recently to the introduction of strains with increased resistance to the viral disease infectious pancreatic necrosis (IPN) (Houston *et al*. 2010). With the imminent arrival of full genome maps for salmon and other major aquaculture species, further major advances are anticipated, e.g. Landcatch Natural Selection is working on selectively breeding for resistance to pancreas disease (PD) (see http://www.landcatch.co.uk/lns/news.html, verified 12 October 2010).

Nutrition

While the development of formulated diets has facilitated the expansion of some types of aquaculture, it is important to note that *c*. 0·25 of aquatic animal production comprises molluscs that rely entirely on naturally available feed. A further 0·50–0·55 is from semi-intensive freshwater aquaculture that uses pond fertilization and supplementary feeds (calculated from FAO 2010). Nevertheless, fully formulated diets have been critical in facilitating the intensification and emergence of major industries such as salmon, trout, sea bass, sea bream, tilapia, catfish and much of the shrimp industry, and will be needed in greater quantities if current trends continue.

Basic approaches to compound feed manufacture were adapted from the animal feed sector, but specialist ingredients and processing have subsequently developed. As feed accounts for 0·50–0·70 of the production cost for intensive species, feed (and therefore ingredient) price is a major constraint (Rana *et al.* 2009). Substantial use has been made of fish meal and oil which most closely match the nutritional requirements of many commercially species and relatively low prices. However, with increasing demand, prices have risen, and as supplies are also finite, vegetable-based alternatives are increasingly being used. These pose a range of challenges including lower levels of essential amino and fatty acids, presence of anti-nutritional factors, processing, palatability and digestibility issues, and wider questions of crop sustainability, land and water use (Torstensen *et al.* 2008). Given the underlying economics, the primary pressure is to develop the most cost effective feed formulation (lowest cost of feed per unit of production). However, this is tempered with environmental considerations (e.g. production of low-phosphorus feeds for use in freshwater, or use of certified organic ingredients in organic production), or final product quality (e.g. selection of type and level of oils in feeds can affect appearance and taste of fish products). There is now increasing specialization of feed formulations to better match the requirements of specific production systems and final markets.

Manufacture of feeds for salmonids is now dominated by three companies, partly due to scale economies in ingredient purchase, manufacture and distribution but also due to use of more advanced technologies which may exclude smaller competitors. These include, for instance, the use of vacuum coating and pellet sealing for increasing and protecting lipid content. This helps to deliver far higher conversion efficiencies of fishmeal to aquaculture produce at lower cost per unit of production (Refstie & Åsgård 2009). Advances in formulation using novel ingredients and synthetic micronutrients are expected to provide further improvements, assisted by greater understanding of the interaction of ingredients with gut microflora and the functional properties of digestive and other enzymes (Austin 2006). The combination of genomic approaches to breeding and diet development could lead to substantial gains in production (cost) efficiency in the future.

Health

The intensification of aquaculture species/systems has been accompanied by increased disease problems with substantial economic impact (e.g. Pulkkinen *et al.* 2010). Major stock losses have been caused by viral diseases especially in the shrimp and salmon sectors while bacterial, parasite and sometimes fungal problems have also affected the production of many fish species. Vaccines have been developed against some diseases in salmonids and marine fish. Most effective have been those against bacterial diseases such as furunculosis and vibriosis, which caused major losses in the salmon industry during the late 1980s and early 1990s. These vaccines were based on killed cells and mineral oil adjuvants and had a major economic impact. For instance, the overall mortality rate for the Scottish salmon industry in 1990 was *c.* 38%, improving to *c.* 12% by 1997 as the vaccines were adopted (FRS 2007). Assuming an average fish value of £4, this represents a loss of >£22 million on the 1990 smolt stocking. Had the same mortality rates existed in 1997, the losses would have been in the order of £44·5 million. Based on a vaccination cost of £0·07 per smolt (Ellis 1989), the cost for this order of benefit was around £3 million. The benefits would have been much greater in Norway where production was substantially higher. The actual effect of this improvement in performance was a reduction in unit production costs (Bjørndal 2002) which, due to competition, led to lower prices and expanded markets.

Unfortunately, survival rates did not remain at 1997 levels in the Scottish salmon industry due to a range of more problematic viral and parasitic diseases. Research efforts have focused on vaccines against viral diseases using a range of more innovative technologies such as DNA/RNA and peptides. Injected vaccines have proved most effective, but can be uneconomic for lower unit value fish. Immersion vaccines provide a partial solution and work is continuing on mechanisms for reliable oral delivery with commercial products now available for some bacterial pathogens (Adams 2009). The most significant disease problem at present for Atlantic salmon is sea lice (e.g. *Lepeophtheirus* spp. and *Caligus* spp.). These are becoming increasingly resistant to a series of treatments, cost the global industry in the region of €300 million per year and significantly influence wild salmonid populations (Costello 2009). The search for a suitable vaccine started over 20 years ago (Alvarez-Pellitero 2008), but new molecular tools appear to be accelerating progress with encouraging results reported by University College Dublin (see http://www.irishtimes.com/newspaper/sciencetoday/2009/1217/1224260826380.html, verified 12 October 2010).

Containment systems

Most traditional aquaculture is based on culture in ponds or lagoons. Floating cages in open water bodies (freshwater or especially marine), tanks and recirculated aquaculture systems are more recent developments. Cage systems have grown in scale (e.g. up to 10 000 m^3/unit) and robustness, and can now be used in substantially exposed conditions (Fredheim & Langan 2009). One of the most common designs utilizes high-density polyethylene pipes (HDPE) that were originally developed for the gas industry, combined with specialized HDPE mouldings. These are moored using specialized anchor and buoy designs, chains and modern synthetic ropes. Knotless nylon netting manufactured specifically for aquaculture is used in most current generation cage nets, but newer materials such as ultra-high molecular weight polyethylene (UHMwPE) are also being utilized. Specialist service vessels such as well boats and catamaran work boats combined with fish pumps, counting and grading systems minimize labour requirements and enable large units to be efficiently stocked and managed (Forster 2008). Floating feed silos with computerized feed delivery systems are evolving into full service platforms with staff accommodation and advanced monitoring and communication systems. Increased company size has been an important factor in technology development, as smaller companies would not have the financial resources to invest in high-capacity equipment or be willing to risk using a small number of larger production units.

Re-circulated aquaculture systems (RAS) offer the potential for aquaculture to be conducted close to market and with minimal environmental discharge. Water treatment technology is largely derived from the waste and potable water treatment industries, but with increasing optimization for aquaculture. RAS provides greater control over environmental variables and improved biosecurity but systems are complex, have high capital cost and have not always operated reliably, making them a higher-risk investment. While there is progress, substantial uptake of RAS appears to be constrained by lack of standard mass-produced low-cost systems (Bostock *et al.* 2008). Equally, without sufficient take-up of the technology, there is minimal incentive or revenue stream for suppliers to invest in the necessary development and manufacturing capacity. Once again it is likely that a threshold will be crossed as larger companies with greater capacity for investment on both sides (aquaculture producers and equipment suppliers) either emerge or enter this field.

In addition to lowering costs and increasing security, systems research and technology development (RTD) is also studying fish behaviour, stress and welfare to help build-in high health (Bondad-Reantaso & Subasinghe 2008). Further progress in computer and sensor technologies are likely to find application in aquaculture to provide better real-time stock management information. Individual (sentinel) fish, for instance, could be fitted with micro sensors/transmitters to provide data on actual environmental conditions being experienced by the fish and any change in physiological parameters. Networking of information between units and farms combined with advances in epidemiology has potential to assist with early detection and warning of emerging disease problems enabling faster management response (Bostock 2009).

Environment

As with most human activity, aquaculture draws upon natural resources and environmental services. Concerns over environmental impacts have shaped and probably constrained development of the sector at least in Europe and North America over the past decade. A central feature of many systems is a reliance on clean, well-oxygenated natural water supplies which are then ‘degraded’ by the aquaculture process, resulting in higher concentrations of nitrogen, phosphorus and carbon and lower levels of oxygen. This can result in measurable changes to the biota at local scales, which can be an issue especially in some freshwater or highly sensitive inshore marine environments (Dempster & Sanchez-Jerez 2008). Predictive models based on solid carbon deposition (marine) or dissolved phosphorus concentration (freshwater) have been developed and are routinely used by regulatory authorities as a basis for determining allowable biomass or production limits (Bostock *et al.* 2010).

Ecological changes resulting from the output of organic and inorganic nutrients are complex and the resulting changes are nevertheless usually within a continuum of naturally occurring environmental/ecological conditions (given all are to some degree impacted by human activities). The examination of cumulative impacts at larger scales is highly problematic, but the potential contribution of aquaculture in relation to biodiversity aspirations is important for future planning (Muir 2005). Direct interactions between aquaculture stock and wildlife are of more immediate concern in some areas. Natural predators of aquaculture species are attracted to farms, prompting owners to employ a range of deterrent or control measures, some of which can be destructive (e.g. the shooting of birds and seals). Technological solutions such as scarers and protective barriers have been developed, although with variable effectiveness (Quick *et al.* 2004). Direct impacts can also occur if the culture stock escapes, e.g. through predation on other species, or displacement of native populations through habitat invasion. More specific concern, especially as species are genetically selected for aquaculture, has focused on the risk of deleterious genetic introgression of native stocks if escapes inter-breed. Most attention has been given to Atlantic salmon, for which McGinnity *et al.* (2003) demonstrated how genetic introgression could lead to reduced whole lifetime fitness and contribute to a decline in stocks. However, actual impacts are likely to be influenced by the number and frequency of escapes and wider characteristics of the environment and local stocks. Genetic marker analysis can be used to investigate populations where this may have occurred and to monitor future changes (Glover *et al.* 2009). In some cases it has been proposed that aquaculture should utilize sterile triploid stock or otherwise develop strains that would not be able to reproduce in the wild (Wong & Van Eenennaam 2008).

The greatest public concern has arguably been over the discharge of therapeutant chemicals into the environment and the risk of residues of these or other potentially harmful substances being present in aquaculture or other food products (Burridge *et al*. 2010). Improved laboratory detection methods have facilitated greater assessment and monitoring in this area, although cost barriers currently prevent widespread routine screening. More sophisticated risk modelling is informing debate and gradually allowing regulators to develop more effective controls and producers to improve disease prevention strategies that reduce the need for therapeutants (Peeler *et al*. 2007).

Management

Key at both company and sector levels is the quality and timeliness of information available to managers. Information and communication technology (ICT) is providing powerful tools to assist with this. For planning and regulatory functions, geographic information systems (GIS) have proved an effective way of not only collating and visualizing but also analysing and modelling a diverse range of information with spatial attributes (Ross *et al*. 2009). Information and communication technology can also be seen to play an important role in modern market chains. Major supermarkets require increasingly sophisticated market models to help predict demand for individual products that incorporate specific short-term variables such as promotions on substitute items that might be known to increase or decrease consumption of perishable products (Taylor & Fearne 2009). This information is communicated to the supply chain in the form of forward orders that are often less than 24 h prior to delivery. Producers therefore need to have excellent planning and logistic information to be able to respond appropriately. In the case of a large salmon company, for instance, this involves assessment of which sites and cages should be harvested to provide the required product, the selection and mobilization of the appropriate processing plant and all the intermediate transport logistics. The ICT systems also provide the tools for food and feed traceability (Bostock 2009).

While the industry itself is making use of complex real-time data for management decisions, regulatory frameworks (which need to be effective – Barton & Fløysand *in press*) are often based on worst-case models and relatively static assumptions of industry performance. If greater data sharing was established, it is conceivable that regulators could develop more responsive systems for sector management. For instance, adapting biomass consent limits in relation to changes in a company's feed specifications, unusual annual weather cycles, or in response to unexpected events such as losses at another farm site.

FUTURE PERSPECTIVES

Social, political and market drivers

The need for increased aquaculture output over the next 20 years is widely forecast based on population projections, anticipated economic development and concern over the future sustainability of capture fisheries (e.g. Brugère & Ridler 2004). Underlying assumptions are that fish and seafood prices remain at approximately similar levels in relation to other proteins, that a majority of the population will wish to continue to consume meat from aquatic sources, and that there is no major production of seafood substitutes using advanced biotechnological processes.

A clear driver for the future is the increased focus on sustainability, which over the past decade has given rise to a broader range of assessment measures for the performance of different food production systems (Bartley *et al*. 2007). These include resource use efficiency or impact indicators, particularly in relation to greenhouse gas emissions. In many cases, aquaculture scores favourably in relation to livestock and even some fisheries or agricultural production systems. Developing aquaculture systems that seek optimum performance across a broader range of sustainability measures is already an aim of many in the sector with the adoption of standards and certification systems (most notably the forthcoming WWF supported Aquaculture Certification Council, http://www.aquaculturecertification.org, verified 12 October 2010). However, economic sustainability is paramount for the industry, and so substantial progress on some measures of sustainability may not be possible without significant policy adjustments at national and preferably international levels.

There is considerable research interest, at least among the academic, governmental and non-governmental sectors, in improving sustainability through better integration of production systems (e.g. Soto *et al*. 2007). Ironically, some of the oldest aquaculture practices are the integrated pond polyculture systems in Southern China. These have long been a model of ecological efficiency and sustainability, although it is only in the last decades that nutrient and energy flows have been quantified. However, many such systems have either disappeared or been converted to intensive monocultures in response to the wider pressures of economic development (Pullin *et al*. 2007). New configurations of ecologically efficient production can be identified and a number of research programmes are addressing the practical constraints to implementation (Soto *et al*. 2007). However, with current accounting methods, secondary products from integrated systems often appear unviable and requiring financial subsidy. This is largely due the fact that there is little (if any) financial value being placed on environmental services. An adjustment in economics to encourage secondary production as a means of reducing the cost of environmental services could fundamentally change the food production landscape (Soto & Jara 2007). Examples of current trials include wide area integrated aquaculture for fish, molluscs and seaweeds in coastal zones, combinations of recirculated aquaculture and aquaponics for freshwater, and multi-compartment pond systems.

Industrial and technology drivers

Although increasing in importance, aquaculture is still a relatively small component of the global agro-food industry. This has tended to limit RTD investment as for instance potential sales of a poultry vaccine would be many tens of times higher than for a salmonid vaccine, which in turn is 10 times higher than the market for, as an example, sea bass. Public funding has been used to help overcome key bottlenecks to commercial production (such as closing reproductive cycles), but with the emergence of international aquaculture companies, has been more focused on wider social concerns of mitigating environmental impacts, improving food safety and promoting sustainability (e.g. see changes to EC RTD priorities for aquaculture discussed at http://www.eatip.eu/content/view/52/111/, verified 12 October 2010). Research and technology development oriented to improving the production performance of the industry is increasingly in the hands of the key suppliers to the production sector; seed, feed, pharmaceutical and engineering supply companies, often working in collaborative relationships with academic and other research organizations and of course in close partnership with their customers. Consolidation within the supply sector has concentrated and strengthened private RTD capacity so budgets for this should grow as the market for their products expands. Consolidation of production has also provided suppliers with a simplified landscape for their marketing efforts, and with customers that have a greater capacity for major investment. Innovation and technological progress is therefore fully integrated into the drivers and mechanisms of globalization and corporate consolidation, although there are also risks that competition and innovation become constricted when large corporations become more focused on market domination.

CONCLUSIONS

Globally, aquaculture is dominated by smallholder and small company production in tropical and subtropical countries (Lazard *et al.* 2010). However, for the products most traded through consolidated international multiple retailers (especially in Europe and North America), consolidation is feeding back through the market chain and creating major international aquaculture companies (e.g. Olson & Criddle 2008). The pursuit of profit and strong competition has encouraged the development and uptake of science-based innovations that have greatly boosted productivity and reduced food prices in real terms. A major success by the economic measures currently employed.

The economic viability of smallholder aquaculture is largely dependent on low costs for labour, land and water resources. Rising population numbers might be expected to keep labour cost low while increasing prices for land and water. On the other hand, global social aspirations appear to lean towards urbanization and less labour intensive and more consumptive lifestyles (Beall *et al.* 2009). While smallholder aquaculture might remain important in many countries for decades to come, in others it may be replaced by more intensive and technology dependent systems as either local or international vertically integrated companies seek additional production capacity. In China, for instance, there is a clear strategy for strengthening aquaculture enterprises and the downstream value chain through technology transfer and modernization towards higher efficiency and productivity (Zhou & Chen 2010).

While rising population numbers, combined with the stagnation of production from capture fisheries, are expected to be the main driver for increased aquaculture production, the nature of market chains, the dynamics of retailing and the aspirations and wants of consumers (albeit influenced by promotional and campaign activities) will play a major role in shaping the future of the aquaculture industry. Future commercial success will be in the hands of innovative companies that are responsive to consumer wants and quicker to adopt new technologies that provide competitive advantage. However, major changes to the external environment could impact significantly on the organization and technologies of aquaculture production. In particular, if the cost of key resources (especially energy) rises, or if currently uncosted environmental services are incorporated further into global economics and farm costs (e.g. Barbier 2009; Wainger & Boyd 2009). Scenarios of rapidly rising energy cost due to scarcity will mitigate against energy-intensive production systems typified by high levels of mechanization and long-distance transport; but a widespread return to low-intensity production is unlikely to be an acceptable option. Radical biotechnology developments may be needed to achieve higher productivities with lower demands on both ecosystem services and energy inputs; although advances in renewable energy combined with enhanced ecological efficiency will also play an important role.

The need for continued investment in RTD and the application of science to aquaculture production is clear, but responsibilities are perhaps more controversial. The current economic constraint on public funds in Europe encourages government to place greater expectations on industry to take responsibility for leading and investing in RTD. The European Commission for instance is promoting industry-led technology platforms (see http://cordis.europa.eu/technology-platforms/, verified 12 October 2010) to both inform research priorities and lead collaborative programmes, hence the formation of the European Technology and Innovation Platform (EATIP; see http://www.eatip.eu, verified 12 October 2010). While the greater focus on industry RTD needs should help accelerate technological innovation, it will probably further reinforce trends towards a consolidated aquafood industry. This will have wider global impacts as long as European (and North American) markets are large net importers of aquaculture produce and if 'Western' market chain models are further adopted in other industrializing regions.

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