Report to the Royal Commission on Environmental Pollution

The potential impact of technological innovation on the aquaculture industry

FULL REPORT

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Executive Summary

Farming of the sea has a long history in many countries, essentially based on a range of modified low-input natural systems, including ponds, shellfish beds and simple enclosures or cages. In the last two decades the intensive farming of marine fish and the scaling up of shellfish culture has been a major trend, prompted by rising demand for aquatic food products precisely when traditional supplies from capture fisheries are in steep decline.

The predominant technology for marine fish culture grows stock intensively on compounded diets in floating cages in sheltered coastal waters. In Europe, marine fish farming grew from 724 to 786,082 tonnes between 1970 and 2000, around 50% of which is in Norway. As it has grown, environmental capacity has been an increasing concern, particularly within inshore waters. There are related concerns for nutrient enrichment and for food safety, in the accumulation of chemical contaminants or biological toxins. Key environmental issues and the steps being taken to address them are outlined in Table S1:

Table S1: Environmental concerns relating to marine fish farming

Issue	Nature of constraint	Solutions under investigation or implementation
Reliance on industrial fisheries for fishmeal and fish oil required for aquafeeds	Intensive marine aquaculture utilises finite (albeit sustainable) supplies of fish meal and fish oil from industrial fisheries. There are difficulties in complete substitution by terrestrial proteins and oils.	The limits of substitution are under investigation. There may be prospects in genetically modified fish, plants or microorganisms, although developments through selective breeding are more likely. Technology to lower the cost of producing omega 3 fatty acids using microorganisms is receiving attention
Organic solids waste produced by fish farms	There can be localised effects on the seabed associated with the accumulation of fish faeces and uneaten food. It is prudent for both farms and the wider coastal environment to limit the degree and extent of such accumulations.	Diets formulated for higher digestibility and lower waste. Feed control systems introduced to optimise feeding and minimise waste. Sites are regularly fallowed to allow natural recovery and more exposed sites are being used to improve waste dispersion. Genetic selection will improve feeding efficiency; Waste collection devices have been tested but their viability remains to be demonstrated
Dissolved organic and inorganic wastes produced by fish farms	Localised effects (mainly enhance productivity of seaweeds and other marine organisms) can be noted. No direct linkage with problematic algal or jellyfish blooms, but needs to be considered within the context of total marine nutrient balance	Research to investigate carrying capacity. Possible integration of shellfish and seaweed culture as biological filters
Discharge of chemicals and therapeutants from aquaculture facilities	Therapeutants are sometimes required to treat health issues. In open marine systems, some discharge into the environment is unavoidable.	Greater use of vaccines and improved health management procedures. Selective improvement for disease resistance to reduce need for therapeutics. Continued work required on new and outstanding health issues and implementation of greater monitoring
Escape of stock from fish farm facilities and other interactions with wild fisheries	Especially a concern with salmon, where farm escapees could interbreed with fragile wild stocks or compete for resources. Also the transfer of disease to and from farmed and wild stocks	Improvements in equipment specification and maintenance; careful selection of sites; area management agreements and coordinated disease treatment strategies. Development of sterile farm strains will reduce introgression from farm to wild strains.
Interactions with predatory wildlife	Predatory birds, mammals and sometimes fish can cause substantial losses at marine fish and shellfish farms. Solutions are required to prevent predation without harming the animals responsible	Various non-destructive anti-predator devices developed; further improvements anticipated

Other marine aquaculture technologies include shellfish beds, trestles and suspended longlines, artificial reefs, and fish release and recapture systems. Intensive onshore tanks are also used, some of which may recycle water. Environmental issues are less critical for these, either because of less intensive or more managed production methods or because production levels are insignificant.

Technological solutions already exist to address many of the concerns expressed about marine aquaculture (Table S2), but higher costs prevent their commercial adoption in a competitive environment. Major breakthroughs in price/performance are only clearly available using genetic engineering, although a major decrease in energy cost could make land-based aquaculture more attractive.

Table S2: Technology options for marine fish farm development

Technology direction	Issues addressed	Issues remaining	Projected development
Continued growth in near-shore cage-based aquaculture, with greater emphasis on coastal zone management and integration of activities	Sustainable development without further environmental degradation	Most to some degree	Gradual expansion, perhaps to 2 million tonnes in EEA countries by 2010 (from 777,000 tonnes in 2000)
Development and uptake of offshore farming	Local coastal zone impacts much reduced	Higher cost, greater risk, both to facilities and to personnel	Gradual investment in more exposed farm sites. Major offshore farm ventures in place by 2010, potential for substantial volumes by 2015 - 2020
On-shore closed recycle systems	Nutrient control, escapees, localised impacts, wildlife interactions, disease control,	Market acceptability, High construction cost, high service charges, Energy use	Used for high value species/stages only, unless major efficiency gains are achieved, energy prices greatly reduced, GM technology becomes acceptable and/or much greater restrictions on cage systems are introduced. Development horizon probably well beyond 2010
On-shore integrated marine aquaculture	Localised impacts, ecological efficiency, reduced nutrients.	Disease control, coastal land availability, predator control, therapeutant usage	Potential for development in some Mediterranean and tropical countries with low-lying coastal land. Products on market by 2010 but overall production in low thousands of tonnes by 2020
Free-range aquaculture, perhaps using hatcheries to restock the sea and using habitat enhancement, feed attractants and training to enable easy recapture using traditional techniques	Nutrient and ecological efficiency, localised impacts, use of existing fishing vessels and skills,	Legal obstacles, undeveloped technology, Unproven economics, possible ecological disruption	Possible avenue for research if traditional fishing access rights and management models collapse. Expected timescale after 2010. Global potential for several million of tonnes by 2050.

These solutions are by no means mutually exclusive, but relative economic performance will be the primary determinant of their uptake, influenced by regulatory policies and consumer preferences. Further development of the sector is certainly anticipated, with the European Commission strongly supporting expansion, albeit with greater emphasis on addressing environmental issues.

Even if it is assumed that capture fisheries supplies are maintained at year 2000 levels, aquaculture production to 2010 is expected to expand at around 4% per year across the EU. The advent of c50% reductions in CFP quotas for key species from 2003 is likely to accelerate the growth of aquaculture supplies. A greater variety of species will be produced, most at relatively low levels, aimed initially at premium markets. Of the marine aquaculture species, only salmon has expanded to the point where it provides lower-priced commodity raw material for a wide variety of food products, although even this is still within the price range of the top 15% of captured supplies in terms of first sale value.

A key factor enabling salmon to be produced at lower prices has been its simple and cheap hatchery technology. Marine species such as cod and haddock have potential, but for the medium term will have high hatchery costs and hence higher prices and more limited market scope. With a major decline in whitefish supply from capture fisheries, species currently targeting large lower-priced markets (eg frozen cod blocks) are more likely to shift to higher-priced market sectors. The resultant void in lower-priced markets is likely to stimulate the adoption of alternative species including lower-cost freshwater whitefish, such as tilapia, which is mainly produced in tropical countries.

The consensus of forward projections proposes incremental developments in engineering, nutrition and disease control, and improvements to stock through selective breeding. This will enable marine aquaculture, within Europe and beyond, to further develop, although most likely to be constrained within the 15-20% premium sector of the total fish and seafood market. The future evolution of this market is uncertain, but anticipated growth in population and per capita seafood consumption suggests European mariculture production could conservatively reach 2 million tonnes by 2005 (including shellfish), 3 million tonnes by 2020 and 4 million tonnes by 2040.

The technology change and related environmental implications of this development are primarily likely to focus around better nutrient management, containment processes, and more effective multi-element environmental monitoring and modelling. Better appreciation of the strategic use of coastal and near-shore environments, in conditions of increased human impact in coastal zones, will lead to better approaches to biosecurity and food safety. Technical issues associated with market traceability will also become more important, and have the potential to form the core of integrated information-rich approaches to aquatic system management. Such attributes are increasingly likely to confer competitive advantages upon aquatic foods over more conventional products, and are likely to become critical determinants of development potential

1. Introduction

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1. Introduction

1.1 Aims and approach

The study examines the environmental issues raised by mariculture[1] technology as it exists at present, and as it may develop over the coming decades. It considers the factors influencing uptake of new or alternative technologies, including commercial, technical, market, and policy drivers. The emphasis is on mariculture in Northern Europe, within the wider European and global context.

Farming of the sea, especially for bivalve molluscs and seaweeds has a long history in many countries. However, the intensive farming of marine fish and the industrialisation of shellfish has mostly developed over the last two decades. The sector is encouraged by increasing demand for aquatic food due to population growth, growing appreciation of its health benefits and by the stabilisation, or in many cases, ongoing decline in capture fisheries production through overfishing and the failure of fisheries resource management. Globally, the share of aquaculture in the supply of aquatic food products is over 25%, and is rising further.

As with any human activity that utilises natural resources, aquaculture has an impact on the environment in which it is conducted. It is also closely dependent on the quality of these environments. In most countries, and certainly within the UK, these relationships have been researched and regulated since the early stages of the industry However, the issues have subsequently been brought to wider public attention and criticism through special interest campaigners, especially in Canada and Scotland. With the debate started, and with the failure of Northern European fisheries management to sustain capture fisheries supplies, it is timely to consider the future development of mariculture in relation to capture fisheries, their synergies and conflicts, and the impact that each have on the environment.

The interactions between aquaculture and the environment may be categorised in terms of the "environmental goods" (natural resources that constitute primary inputs to the aquaculture production system, such as land, water, oxygen, fuel and raw feedstuffs) and "environmental services" (physical and ecological processes that deal with the waste outputs from aquaculture) that are utilised by aquaculture. At modest levels, the impact of aquaculture may be relatively undetectable. However, with increasing levels of activity, changes in the environment are observed, as ecosystem balances shift to compensate for the goods that are being removed, or the wastes that are being discharged. The degree of change is dependent on the scale of aquaculture inputs and outputs and the extent to which they are localised or dispersed. This leads on to the commonly expressed notion of carrying capacity, where the scale of aquaculture operations are constrained by site specific consideration of environmental supply/servicing capacity. However, this is exceedingly difficult to define in practice due to measurement constraints and the need to agree acceptable degrees of environmental or ecological change. In most countries, and certainly within the UK, these relationships have been researched and regulated since the industry commenced. However, the issues have been brought to wider public attention through special interest campaigners, especially in Canada and Scotland. With the debate started, and with the failure of Northern European fisheries management to adequately sustain capture fisheries supplies, it is timely to consider the future development of mariculture in relation to capture fisheries, their synergies and conflicts, and the impact that each have on the environment. This report aims to be objective and draws on the best available research evidence when discussing issues. Where appropriate, discussion is guided by a general principle of support for sustainable development. The following definition was adopted by the 94th FAO Committee on Fisheries in 1991:

1 Mariculture is the farming of aquatic plants and animals, especially fish and shellfish, in the marine environment.

"Sustainable development is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such development conserves land, water, plant and genetic resources, is environmentally non-degrading, technologically appropriate, economically viable and socially acceptable."

The report commences with an overview of the development of the aquaculture industry, followed by a more detailed examination of the technologies that have been developed to solve its management objectives. At this point we also examine implications for the environment of using those technologies, and the ways in which they may evolve further over the coming decades. We then consider the future shape of the industry within the wider external environment and the potential interactions between innovation, consumer aspirations and societal needs. The various elements are brought together to consider the opportunities and constraints that face different types of marine aquaculture system. Finally, we review key industry trends, using these to set out the nature and rate of change over the forward period. The analysis is based on the processes of change within the commercial subsectors, their use of technology within a competitive context, and the policy and regulatory interactions they face, rather than on the assumption that scientific findings and technical applications alone would drive change.

1.2 The rationale for aquaculture

The World Fish Centre[2] and the International Food Policy Research Institute recently reported that global per capita fish consumption had doubled over the past 50 years, and that fish production would need to double to keep up with demand over the next 25 years. However, supply from capture fisheries is at best static, with most wild stocks already heavily depleted, over-fished or fully exploited. Aquaculture production has increased tenfold over the past 30 years in response to market opportunities, and in 2000 supplied around 27% of fish, crustacean and mollusc products (35.5 million tonnes), although only 2 million tonnes of this was marine fish, representing 2.7% of total marine fish supplies (4.8% of marine fish for human consumption) (FAO, 2002). Continued growth in aquaculture therefore appears likely, although not without raising issues of natural resource utilisation, environmental effects and social equity. These are increasingly critical attributes influencing many seemingly simple food-choice decisions. Welfare gains are also to be realised through the generally accepted health benefits of consuming more aquatic foods, with a range of positive dietary effects increasingly recognised and valued by consumers.

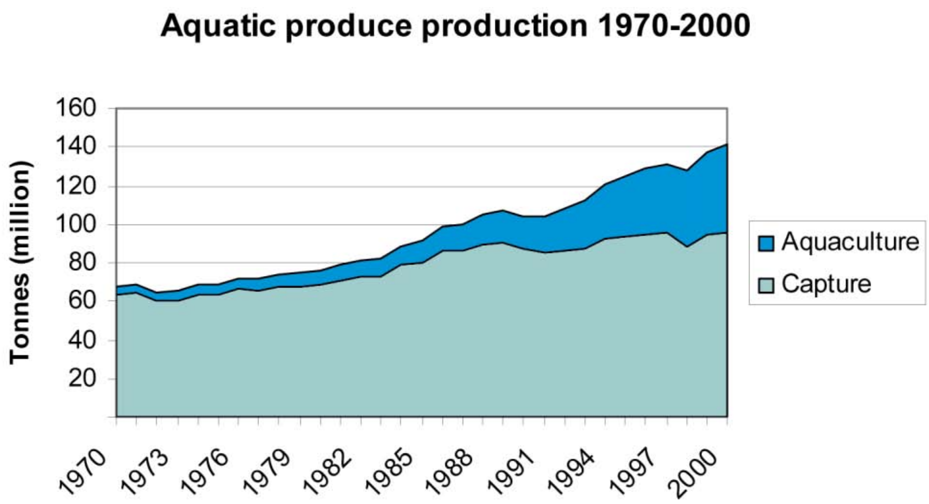

Figure 1.1 The increasing contribution of aquaculture to total aquatic product supply (includes fish, shellfish, and seaweeds)

2 Formerly ICLARM – International Center for Living Aquatic Resource Management

Whilst overall trends are clear, the aquatic food sector is highly diverse and countertrends can also arise. Although aquaculture growth is a broad theme, many segments are either stagnant or in decline; to be expected as new products establish their plateaux, decline and are vulnerable to yet newer versions. Products may be identified at various points on a continuum between low-price commodity protein source and high-unit-value luxury product. The same species basis, possibly the same product, might appear at different points on this continuum in different markets, although global trade will tend to moderate these effects. As with all products, price is ultimately set by the balance of supply and demand, with demand a more complex function of consumer choices. However, in broad terms, carnivorous fish tend to be preferred over herbivorous fish, which has significant ecological consequences. Aquaculture tends to focus on higher-unit-value species (at least within a specific social context), although increasing production will tend to push prices down until there is little further scope for reduced cost of production. Many species are not cultured as the market price is well below likely production cost, due to the existing supply from the capture fishery. The culture of such species is only likely once market prices significantly increase, or new technologies that reduce the cost of production are introduced.

1.3 Aquaculture in Europe

Aquaculture production (fish and shellfish) in the EEA 18 countries has quadrupled from 1970-1999, from 417,979 tonnes in 1970 to 1,852,875 tonnes in 1999, worth around £3 billion (average £1619/ tonne). The five largest producers (in terms of output in 2000) were Norway, Spain, France, Italy and the UK. For France, Spain and Italy especially, most of this is shellfish culture, whereas for Norway and the UK, this is primarily based on Atlantic salmon. During the same period, fisheries landings have oscillated considerably, but overall have fallen from 7.6 to 6 million tonnes, meaning that aquaculture has more than covered the shortfall. Nonetheless, the European Community is required to import more than 50% of its supplies (by quantity).

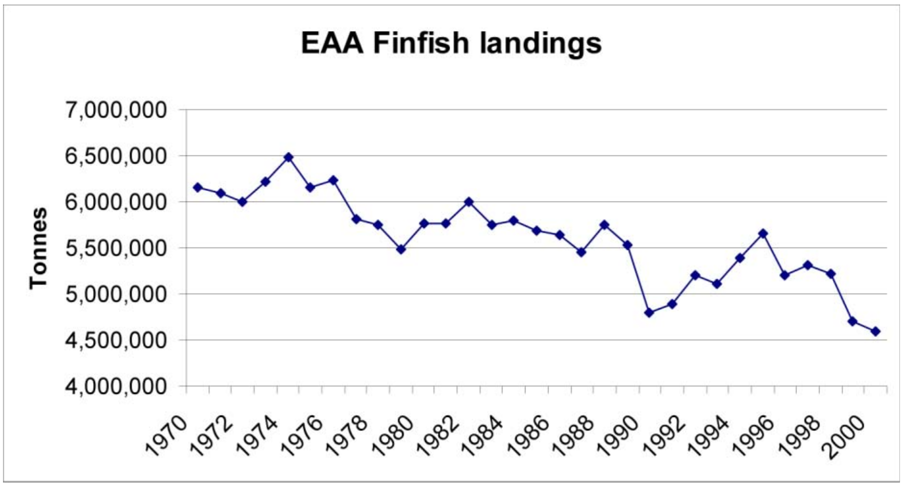

Figure 1.2: EAA marine fin fish landings 1970-2000

Table 1.1: Total aquaculture production (fish and shellfish) in tonnes for EEA-18 countries (EC-15 minus Luxembourg plus Norway, Faeroe Islands, Iceland and the Channel Islands).

Country	1996	1997	1998	1999	2000
Norway	321,516	367,617	410,748	475,830	487,920
Spain	231,633	239,136	315,477	321,145	312,171
France	285,526	287,243	267,855	264,850	267,767
Italy	189,373	195,719	208,625	210,368	216,525
United Kingdom	109,901	129,715	137,421	154,800	152,485
Greece	39,852	48,838	59,926	79,474	79,879
Netherlands	99,871	98,210	120,094	108,785	75,339
Germany	75,237	59,433	67,020	73,567	59,891
Ireland	34,925	36,854	42,375	43,856	51,247
Denmark	41,924	39,697	42,368	42,670	43,609
Faeroe Islands	17,584	22,538	20,558	39,507	29,297
Finland	17,659	16,426	16,024	15,449	15,400
Portugal	5,364	7,185	7,536	6,268	7,538
Sweden	8,267	6,709	5,504	6,035	4,834
Iceland	3,687	3,663	3,868	3,897	3,623
Austria	2,952	3,021	2,912	3,070	2,847
Belgium	946	846	846	1,597	1,641
Channel Islands	191	130	196	249	390
Total	**1,486,408**	**1,562,980**	**1,729,353**	**1,851,417**	**1,812,403**

Source: FAO

Of the 1.04 million tonnes of EEA fish production in 2000, 237,000 tonnes was freshwater fish (predominantly trout and carp) 676,000 t was salmon and trout reared in seawater, and 101,000 t were other marine fish (mainly sea bass and sea bream in Southern Europe). However, the species range is gradually being broadened as either technical constraints are overcome, or as production economics become viable. These include turbot (4,785 t in 2000), halibut (435 t), cod (167 t) and other Mediterranean species (5,800 t). The 666,000 t of shellfish that were cultured in EEA countries in 2000 comprised mussels (500,000 t), oysters (148,600 t), scallops (191 t), clams and cockles (14,500 t) and others (600 t). Spain is the leading European producer of mussels with 247,730 t in 2000, mainly from Galicia, in the NW[3]. Mussel production is increasing in the UK, with 11,107 t produced in 2000, up from 5,801 t in 1995. As the growout of shellfish relies on natural productivity, the industry is dependent on good sites and freedom from pollution and harmful algal blooms. Overall capacity for expansion is potentially more limited than with fin fish, although there may be further synergies to be obtained (Section 4.1). Prices and margins have also been relatively low, thereby limiting sectoral investment, but these have gradually increased in real terms, associated with stronger and more diversified products and markets. Together, these factors suggest gradual rather than dramatic rises in production.

1.4 The global context

The global patterns of fish production owe much to the activities of China, whose reported production by volume accounts for 32 % of the world total. Other major producers are Japan, India, the United States, the Russian Federation and Indonesia. European production represents just 3% of world aquaculture by volume. In Asia, much of the production is from traditionally based aquaculture systems that are integrated into wider farming systems. Such aquaculture, including enhancement and culture-based fisheries, has made significant contributions to the alleviation of poverty, through improved protein supply for domestic consumption, income generation and the provision of employment. However, intensive aquaculture has also developed in Asia, especially coastal shrimp farms, and more recently larger-scale freshwater and marine fish farming utilising ponds, tanks and cages.

3 At the time of writing under potential threat from the sinking of the 'Prestige'

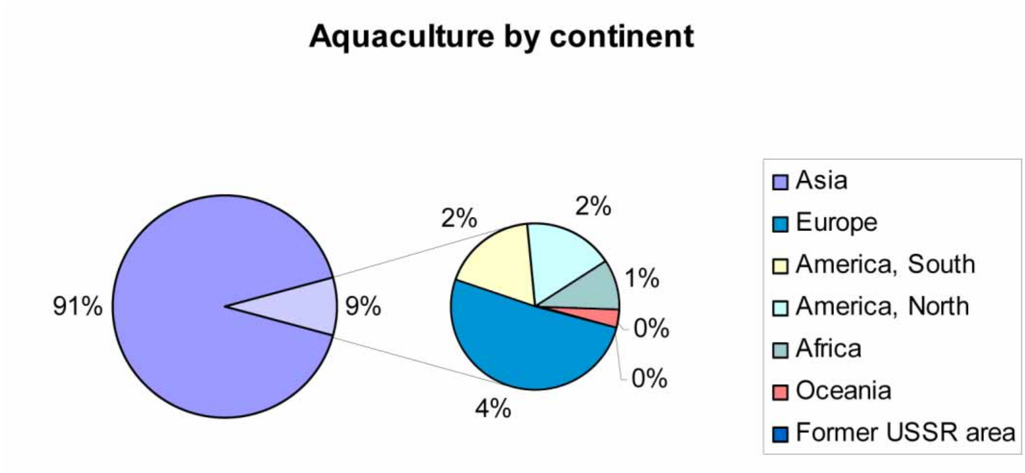

Figure 1.3: Aquaculture production by continent, showing the dominance of Asia, with Europe accounting for around 4% of production in 2000

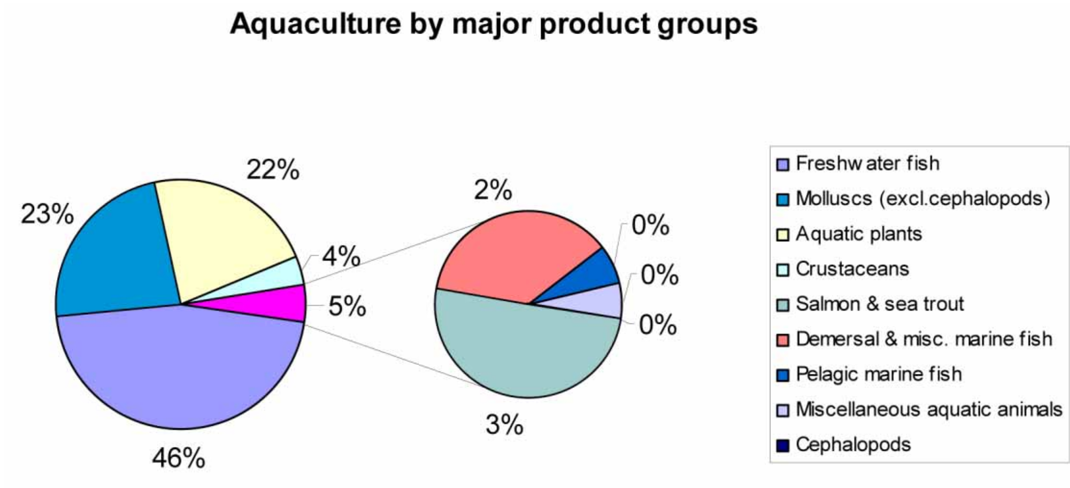

Figure 1.4: Aquaculture by major product group, showing marine fish culture at around 5% of total aquaculture production by volume in 2000

Country	1995	1996	1997	1998	1999	2000
Finfish						
Asia	13,484,358	15,306,133	16,858,807	17,829,736	19,318,022	20,482,334
Europe	881,213	943,287	1,021,647	1,095,411	1,233,821	1,253,934
South America	216,053	299,476	370,828	396,423	404,725	536,698
North America	349,119	387,251	440,461	456,286	511,011	519,171
Africa	95,394	112,792	118,393	176,648	266,005	384,337
Oceania	15,654	19,151	17,850	21,901	24,726	28,763
Total	15,041,791	17,068,090	18,827,986	19,976,405	21,758,310	23,205,237
Shellfish						
Asia	8,228,922	8,511,281	8,610,777	9,180,924	10,318,376	11,168,554
Europe	694,153	717,123	712,366	820,132	823,689	768,873
North America	209,881	179,814	200,493	208,276	222,650	178,748
South America	144,238	151,393	186,842	212,424	212,184	155,174
Oceania	78,583	82,546	87,453	102,214	104,669	100,649
Africa	4,899	5,280	6,589	6,824	6,933	7,876
Total	9,360,676	9,647,437	9,804,520	10,530,794	11,688,501	12,379,874

Source: FAO

The overall value of cultured fish and shellfish in 2000 was around US$56 billion, of which $31.5 billion was due to fish and $18.8 billion to shellfish (including shrimp). By volume, 58% was from fresh/inland waters 6% from brackish water (mainly shrimp), and 36% from marine waters. Of the marine production, 82% related to molluscs and only 15.6% to fish (1.15 million tonnes of salmon and trout and 856,600 tonnes of marine fish), although fish accounted for 40% of value. Coastal (marine plus brackish water) aquaculture is generally growing more quickly than inland aquaculture, albeit from a lower base. More significantly, coastal fish and shrimp production is dominated by commercial enterprise whilst freshwater aquaculture has a substantial contribution from smallholder producers. The commercial funding of coastal aquaculture is an important factor in facilitating more rapid technology development, as is its more common uptake within international trade.

2. Aquaculture Technology Issues

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2. Aquaculture Technology Issues

2.1 Introduction

The technologies used for marine aquaculture are a response to objectives that seek to optimise the management of a number of varied and simultaneous constraints. This section describes these objectives, discusses key constraints, and thence the types of technology that have been developed, or are under development, to overcome them. Finally the environmental issues associated with particular technologies are considered. This enables environmental impacts to be considered within a broader context of marine production and ecosystem management.

As almost all aquaculture is commercially driven, the primary objective is to achieve a realistic financial return. Like agriculture, aquaculture has long production cycles; dependence on climatic conditions; has a strong element of natural resource use and delivers a perishable product. It differs radically from fisheries in that it is based on making direct interventions in the life cycle of the target species in order to enhance production. The key interventions (noting where they relate only to fish or shellfish) are:

- A containment (fish) or attachment (shellfish) structure that provides space and favourable environmental conditions for the animals to develop and grow whilst constraining their wider movement (fish), provides protection from predators and other harmful elements, and that facilitates complete harvests at the chosen time. It also implies a suitably serviced site to locate the structures.
- The provision of nutrition (fish) to enhance growth rates and increase utilisation of containment structures. This may range from stimulating natural food production through introducing various types of fertilisers and manipulation of the physical environment, through to the provision of a complete compounded diet.
- Control over the reproductive cycle to provide a reliable supply of stock for cultivation, to enable more consistent production that is less dependent on seasonal cycles and to facilitate genetic improvement to domesticate and improve their efficiency as farmed animals.
- Management of stock health and welfare to help avoid disease problems and to provide therapies when outbreaks occur

Technology solutions help facilitate these interventions, with different species requiring differing levels of technological input.

Level of technology use	*Engineering*	*Feeds*	*Genetics*	*Disease management*	*Environmental management*
High	Salmon Halibut Cod/haddock Oysters	Halibut Cod/haddock	Salmon Halibut Cod/haddock	Halibut Cod/haddock Trout	Salmon smolts Oyster Marine fish Scallops
Medium	Trout Scallops	Salmon Trout	Oysters	Salmon	Trout
Low	Mussels	Mussels Oysters Scallops	Mussels Scallops	Mussels Oysters Scallops	Mussels

Table 2.1: Technology use in hatcheries

	Engineering	*Feeds*	*Disease management*	*Environmental management*
High	Salmon Halibut Cod/haddock Oysters	Salmon Halibut Cod/haddock Trout	Salmon Halibut Cod/haddock Trout	Turbot (tanks)
Medium	Trout Mussels Scallops	Tilapia	Tilapia Carp Shrimp	Trout Salmon Marine fish
Low		Mussels Oysters Scallops	Mussels Oysters Scallops	Mussels Scallops Oysters

Table 2.2: Technology use in growout

The implementation of technology solutions are also constrained by basic economic principles, policy instruments and commercial strategies, which are examined in more detail in the next section.

2.2 Secure containment and protection of stock

2.2.1 Design objectives for physical containment systems

Containment systems can be water-based, such as floating cages and pens, or land-based, such as tanks and ponds. The need to maintain good environmental conditions for the stock generally means a requirement for a flow of water through the containment system. Water-based systems normally utilise natural currents flushing through net walls. Land-based systems may be able to use gravity or tidal supplies, or will require a pumped supply. The requirements for bivalve molluscs are similar, in this case a containment or *attachment* structure, and a flow of water which provides natural food as well as oxygen. Sites that supply these resources at relatively low cost can be limited in many locations. Farms usually consist of a number of separate holding units to facilitate management of different batches and life stages. For most fish species, rearing is split into three or more phases.

- The hatchery phase where broodstock are spawned, eggs are hatched, and larval fish are weaned onto artificial (usually dried) diets; requiring the most controlled and protected facilities;
- The nursery phase, where small fish are reared to a suitable size for transfer to larger facilities
- The growout phase of production, leading to harvest.

The dimensions of the units are related to the overall scale of production, with smaller units used for hatchery and nursery phases and larger units for growout. Future technology development is likely to be in materials, equipment and control systems that allow expansion of scale and improvements to efficiency and reliability. Research has been conducted into other types of containment system, such as bubble or acoustic barriers, which may have application in some circumstances. However, radically different approaches to those described here cannot be easily foreseen.

Land-based systems

For tank systems, the most critical element is the maintenance of water flows to replenish oxygen and remove expired carbon dioxide and excretory products. Water treatment equipment may also be used to improve water quality or to facilitate re-use of the water. This includes heating or cooling; degassing to remove excess nitrogen or carbon dioxide; oxygen addition using aerators, oxygenators or bulk-supplied oxygen; physical filtration or sedimentation to remove suspended solids; biological filtration to nitrify ammonia and reduce dissolved organic compounds; and sterilisation using UV light or ozone. High reliability is required from pumps and water treatment equipment, as failures can quickly lead to stock loss. Microprocessor-based monitoring, control and alarm systems are commonly employed, with backup equipment including emergency generators. Future technological development should improve efficiency and reliability, increase scale and reduce unit cost, but will continue to respect the basic principles discussed here. The directions in which this might lead are discussed further in Section 4.

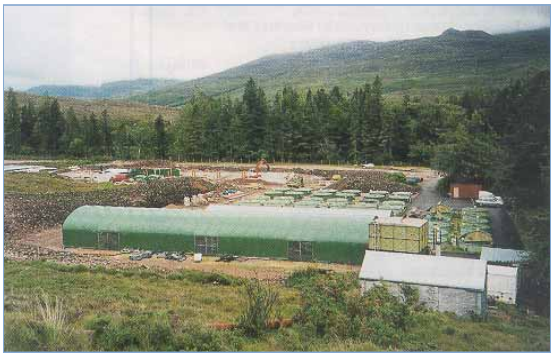


Figure 2.1: A tank-based hatchery (left) and indoor recycle system (right)

Water-based systems

For water-based systems the engineering challenges are entirely different. Moored structures in the marine environment are exposed to highly dynamic forces, so maintaining structural integrity is the primary requirement; there is generally little opportunity to control water quality through engineering measures. Most fish cages comprise of a buoyant collar, from which a net bag is suspended, and a shock absorbing mooring system. Cages are commonly moored in a raft or grid arrangement, sometimes with additional floating work platforms and feed stores. Early cage collars were square (e.g. 3-4 m) and constructed of wood with high-density polystyrene floats. Second generation cages used steel in place of wood, leading to rectangular designs (up to 20m) with improved workspace. However, steel is highly prone to corrosion and weakening in the marine environment, and as a rigid material, great stresses are placed on joints and attachment points, which consequently need to be well engineered to avoid failure in storm conditions. Circular cage collars (10 – 50m diameter), constructed from two or more concentric plastic pipe rings, are a third approach. Early models were prone to UV damage and still used a significant number of steel components. Recent models with improved plastics, moulded components and structural handrails, have proved very robust, with wave energy absorbed throughout the structure, rather than focused at corner joints. Rubber oil hoses inflated to high pressures have also been used for cage collars, proving especially suitable for very large and offshore cages, where their inherent flexibility dissipate impact, flexing and bending forces. More recently, frameless cages, based simply on surface float-lines held open by mooring connectors, have proved workable in exposed conditions. Nets for all types are commonly made from knotless nylon of varying mesh sizes and twine thickness. The mesh size needs to be small enough to retain the fish, but large enough to allow sufficient exchange of water through the pen. Depths range from 5 to 30 meters or more, with weights used at the bottom of the net to help maintain shape. Designs are increasingly sophisticated with some sections providing shock-absorbing properties, others designed to prevent damage through abrasion, whilst the main panels are required to maintain good water exchange and bag shape. The bottom of the net is held in position through the use of a weighted "sinker tube" on circular cages. Submersible cages have also been developed and may be a more common feature of future cage systems if expansion into more offshore environments is required.

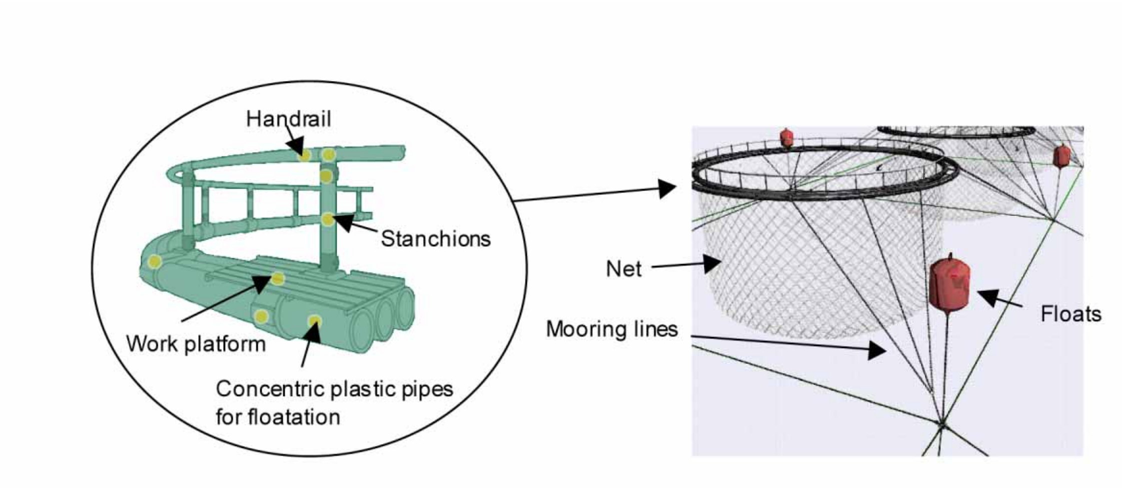

Figure 2.2: Plastic cage components showing detail of collar (from Aqualine AS and Fusion Marine)

Mussel farming uses either floating rafts (traditionally constructed of wood) or long lines (ropes) suspended from individual floats. To the raft or long line are attached a series of rope "droppers" to which the mussels are attached. Key issues include maintaining sufficient buoyancy as the stock is growing and increasing in weight; preventing shock movements that might dislodge the stock from the ropes; and avoiding component failure that would lead to the stock being deposited on the sea floor. Floating platforms may be used for harvesting and other stock management procedures, but are rarely permanently moored. At the present time, equipment for semi-submersible mussel farming is being tested on a pilot scale, and more advanced equipment for management operations such as re-laying mussel spat and harvesting are also being introduced. A number of alternatives to traditional pegged ropes are also now on the market, with further development possible in the future. Other types of shellfish culture may replace the rope droppers with lantern nets, e.g. for the cultivation of scallops, or may be semi-landbased using trays or attachment poles in the intertidal zone. A key constraint for these approaches is that they are very labour intensive, hence future development is most likely to address this issue through mechnisation.

Table 2.3: Summary of main types of aquaculture system

Aquaculture systems	***Feed system options***	***Use in Northern Europe***	***Other use globally***
Finfish& shrimp			
Moored cages suspended from floating collars in open water	Automatic pneumatic or hopper-based feed systems, or manual feeding by hand or canons	Salmon, cod, trout, halibut	Sea bass, sea bream, grouper, tuna, yellow tail, tilapia, coiba, snapper
Fenced areas of open water, or "pens"	Usually hand fed	None	Mainly freshwater in Asia (tilapia)
Onshore tanks with gravity (freshwater) or pumped (marine) supplies, or with water recirculated through treatment equipment	Usually automatic feeders	Hatcheries for Salmon, cod, trout, halibut, growout for eel, sturgeon	Turbot, murray cod, shrimp (especially hatcheries)
Onshore ponds with gravity, tidal or pumped water supply	Automatic or hand feeding	Trout (freshwater), carp	Shrimp, tilapia, crabs, carps
Shellfish			
Onshore tanks (pumped with water treatment/recycle)	Live feed systems	Oyster hatchery	Abalone
Suspended ropes or baskets from longlines or rafts	N/a	Mussels, queen scallops	
Trays or poles in intertidal zone	N/a	Mussels, oysters, clams	
Sub-tidal seabed layout	N/a	Scallop	(lobster ranching)

A number of environmental issues relate directly to the physical design and development of aquaculture containment facilities (excluding resource issues that are dealt with later in this section), mainly concerning interactions with wildlife and other aquatic marine organisms. These include predators, escapees and fouling organisms.

2.2.2 Predators

Predators and scavengers cause considerable direct and indirect problems for aquaculture, including killing or wounding of cultured organisms, increased stress and disease transfer. Predators include species such as squid, fish turtles, lizards, sea snakes, birds and mammals associated with the aquatic environment. Predators are present at most farms due to the ready supply of food or, in the case of marine cage aquaculture, to wild populations of fish attracted by uneaten food waste. Cages may also serve as a roost or observation site for opportunistic scavengers. Although there have been several studies on predation in aquaculture, there are few reliable figures on the economic impacts. However, it has been estimated that predator related losses for the Scottish salmon industry in 1987 were £1.4-1.8 million (Kennedy, 1994), whereas in British Columbia for 1996 this was estimated at $10 million.

The main approaches to predator management (minimising the economic impact of predators) are exclusion (predator netting and other physical barriers), harassment (acoustic deterrent devices, scaring devices and guarding) and removal (licensed shooting, trapping). Removal methods are rarely considered appropriate, and therefore not a key target for technology development. Most outdoor farms deploy perimeter fences to protect against terrestrial predators and wires or netting over fish tanks, ponds and cages to protect against predatory birds. For water-based farms, underwater netting (on sides and occasionally bottoms) may also be necessary, for instance to protect mussel farms from eider ducks, or fish farms from diving birds and sea mammals. They can be reasonably effective if correctly sized and installed, but can be destructive if predators are caught in the netting. Scaring devices (usually acoustic) can be used against dolphins, seals, otters and bird predators. Acoustic deterrent devices (ADDs) are reportedly effective for up to two years, though this appears to diminish with time. This is especially so with seals who tend to learn through previous hunger and successes that these intense signals can be withstood. Long-terms impacts of ADDs on marine mammals are not conclusively known. However, seals and sea lions that are not deterred by the devices may experience hearing damage at close range. These sounds may also interfere with communication signals between animals and with passive listening abilities. The devices have also been linked to declines of baleen and killer whales, leading to a ban on their use in British Columbia, Canada. The mode of action for all acoustic scarer systems are largely the same. Acoustic pulses are generated to propagate away from the fish cages, usually from multiple tranducers with overlapping fields, at sufficient intensity to cause discomfort to any approaching marine mammal. The scarers usually provide up to 3000 m^2 of protection. More complex, modern systems provide a "ramp up" of current from a initial lower level to warn human divers in the vicinity and remove the chance of hearing loss in mammalian predators. Acoustic scarers for birds mostly involve sudden loud noises, with similar problems of habituation and greater issues of sound pollution. Also available for birds is a laser rifle that scares rather than killing or wounding, which may suggest avenues for further technology development.

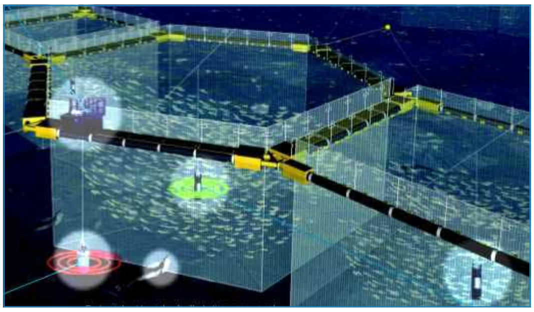

Figure 2.3 Acoustic deterrent device from Ace Aquatec that only triggers when an attack is in progress (http://www.aceaquatec.com/Products/ANSS/anss.html)

2.2.3 Escapees

Of even greater priority to farmers than protecting stock from predators, is that of preventing their escape from the culture facilities. However, especially with water-based and flow-through landbased systems, complete containment is very difficult to achieve in practice. There is an almost continual release of low numbers of animals during day-to day operations such as stocking, grading and disease treatment, alongside occasional mass releases due to storms, predator damage and accidents. Information of the quantity of escapes is limited, as in most countries there is no statutory requirement for reporting these. Beveridge (1996) estimated up to 1.5% of fish stocked in cages escape. Performance is reportedly improving (e.g. Scottish Quality Salmon have introduced a new code of conduct and target of zero escapes) nevertheless, a reported 411,433 salmon escaped from Scottish farms in 2000, whilst 613,000 salmon and trout are through to have escaped Norwegian farms in 2002, and around 900,000 (4,500 tonnes) in Chile (Source: Intrafish).

There are three main implications of interaction between escaped, cultured organisms and their wild counterpart; abiotic (habitat damage), biotic (increased competition and predation) interactions and genetic introgression between farmed and wild stocks. The former is rare in aquaculture introductions, the most obvious example being that of grass carp introduced to the Mediterranean Sea (Beveridge *et al*, 1994). These carp feed voraciously on plant material and thus affect plant biodiversity and wildlife habitat. However, grass carp do not breed in the Mediterranean, thus limiting potential for damage. Introduction of the red-clawed crab to agricultural areas in Portugal and Spain, on the other hand, has caused considerable damage to irrigation ditches and loss of rice production (Beveridge, 1996). The risk of abiotic and biotic damage is perhaps of greatest concern if the cultured species are exotic to the farm location. Approximately 200 aquatic species are currently farmed, but aquaculture still relies on a few for the bulk of its activities due to "know how" and assured markets. As a result these species have been widely translocated around the world, and inevitably have escaped into the local environments, although numbers are much less certain. Mussel farms should also be considered a potential source of introduction of farmed animals, for example all the shellfish introductions to the Mediterranean may now be found in the wild.

The escape of salmon is especially sensitive and can occur at all stages of their life cycle with low numbers potentially surviving to breed with local populations. The general fitness of farm escapees for survival in the wild is often much lower than animal raised under natural conditions be they from wild or farmed strains. The hatchery environment can result in lower levels of physical fitness and changes in behaviour related to feeding (Deverill *et al*, 1999) and territoriality. The magnitude of these changes is proportional to the time the animals spend in the hatchery or farm environment, such that the reproductive fitness in the escaped fish is generally lower than in native fish because of behaviour deficiencies at spawning (Youngson *et al*, 2001). An exception appears to be case of precocious male salmon parr. These are male salmon that mature whilst they are still in the initial freshwater phase of life and as a consequence do not migrate to sea, instead swimming with the adult females and attempting to spawn with them. Natural populations have a small and variable proportion of precocious male parr which are thought to be a component of the overall survival strategy of the species. Recent work by Garant *et al* (2003) confirms earlier concerns that precocious male parr of farmed origin are reproductively more successful than their wild counterparts. This suggests there could be an increased risk and rate of genetic introgression should there be significant escapes from salmon hatcheries or freshwater cage units. Although escapees from marine cages appear less likely to breed successfully, there are concerns that high numbers of such fish may "swamp" the native stock and lead to genetic dilution (Youngson *et al*, 2001). Estimates from the Faroese fishery for salmon indicate that between 20% and 40% of the caught salmon are of farmed origin and 50% in Norway (Hansen *et al*, 1999). While under some circumstances such changes may lead to reduced fitness and productivity, the widely reported declines in wild stocks are almost certainly due to a complex interaction of factors, including over-fishing, habitat destruction and climate change (Beveridge, 2001). The effect of escapees on the native genepool are difficult to assess. Some think that escapees may help to increase or maintain genetic diversity in areas where this is on the decline. The effective breeding size in some natural populations in small river systems may be low and may suffer from problems of inbreeding so the addition of genes may be beneficial. The opposite opinion is that salmonid populations being reproductively isolated are naturally adapted to a given river and the introduction of new genes will damage these gene complexes and reduce the long-term fitness of the population. The truth is probably some where between, it is difficult to show any significant differences in fitness between different salmon populations over small geographic distances, This is not unexpected since Atlantic salmon populations have had a relatively short period to adapt to a given drainage as the populations have only been established in the period since the last glaciation (6000-10000 years). However the species does show a wide range of survival adaptations and life history strategies and that more of these are displayed in larger populations. Small west coast rivers generally have small grilse stocks whereas large east rivers have grilse and multi-seawinter fish returning in most months of the year. This would suggest that these different strategies have been under some natural selection. However genetic studies on farmed fish do show that environment and feeding success can change the relative proportion of these different life strategies in farm populations. In salmon a single geneotype may have several potential phenotypes. In Finland genetic diversity of wild stock is being enhanced using captive breeding methods with 11 stocks of salmon (Koljonen *et al*, 2000). In general this issue is likely to be of lower concern for other marine species such as cod, haddock and halibut, which generally have much larger population sizes and ranges. Early studies comparing different natural populations for commercial potential will help to identify whether there is any genetic differentiation between putative natural populations. As escapees are also highly undesirable from the farmers perspective (direct economic loss), the technological improvement of containment systems and improved management and maintenance appear the best way to minimise this issue. For instance a Norwegian company[4] has recently launched a new net lifting system that uses electrical winches integrated into the cage design, which it claims reduces stresses on the net and therefore the risk of net failure and fish escapes. Where physical containment proves impossible, sterilisation (see Section 2.4.3), as a form of genetic containment, is another option for preventing genetic contamination.

2.2.4 Fouling organisms

The growth of attached aquatic organisms (e.g. seaweed, barnacles, mussels, tunicates etc.) to marine structures is a significant management problem. They increase the weight of floating structures, but more importantly, they block the mesh of nets, reducing water exchange, and reduce the diameter of pipes, reducing flows and increasing pumping costs.

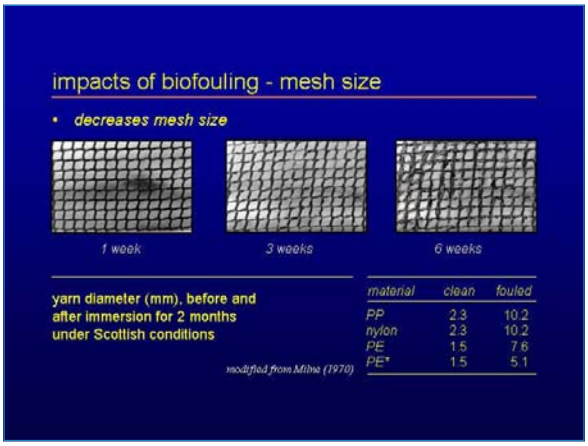

Figure 2.4: Impact of fouling organisms on nets – reducing effective mesh size and hence water exchange

4 Atlantic Cage Systems Inc. (Further details at http://home.monet.no/~preplast/ (in Norwegian) or Fish Farming International, 2003, Vol. 30 No. 8 (August), page 32)

Control of fouling organisms is usually in the form of a slowly released biocide into the water. This ensures that the more susceptible juvenile stages of the organisms cannot settle (or are inhibited from settling) on aquaculture structures. This is particularly problematic for marine fish cage culture. The present anti-foulants are mainly copper based, usually in the form of native copper, copper oxide or copper sulphate (e.g. currently, 19 of the 24 antifoulant products registered for use in Scottish aquaculture). While marketing of antifoulants in Europe is controlled (in Scotland by the Health and Safety Executive) and their use must be included on discharge consents, as copper is listed under the EU Dangerous Substances legislation, there is no evidence that they are directly harmful to fish or contaminate fish flesh. Copper released usually binds strongly to particulate materials within the water column and falls to the seabed. It therefore tends to accumulate within sediments near to fish cages. There is little evidence that this is bioavailable to marine organisms or transmitted through the food chain, as it is present in organic form which is not directly toxic.

There are constant moves, supported by industry, to reduce toxic anti-foulant use in aquatic environments. New materials are under investigation and some at marketable stage. These tend either to use natural repellents, such as capsicum derivatives, enzyme based derivatives or slow fouling material, such as polyurethane polymers or Teflon coatings where the foulants cannot find purchase on the netting. Future materials may make use of nanotechnology. Early results in large scale field trials of many of these anti-foulant mechanisms, have been encouraging. Their use is likely to be extensive in the aquaculture industry in the future, potentially negating the use of toxic copper based substances. Little is known of the environmental implications of the natural repellents, as the only data available is from manufactures own marketing information.

2.2.5 Materials

Farms are using an increasing amount of plastic equipment on grounds of cost and robustness. Most cage collars are now plastic (mainly polyethylene) and mussel farms use large numbers of plastic (also polyethylene) floats. Most nets are made of polyamide (nylon), which is also used in ropes, as well as polypropylene and polyester. Plastics are also used extensively in hatcheries, in the form of glass reinforced plastic (GRP), polypropylene and polyethylene tanks, PVC, ABS and polyethylene pipes. Disposal at the end of equipment service life currently relies mainly on landfill or possibly incineration, although certain plastics can now be recycled. Galvanised steel was extensively used in second-generation aquaculture cages, but is less important now, although still used for some key structural and mooring components. Again, this can be recycled through established scrap metal businesses. Compared with other sectors, the aquaculture industry does not generate large quantities of material waste, but shares generic disposal/recycle issues relating to vehicles, batteries, lights, electronics, lubricants etc. The lifecycle of major equipment is in the region of 10-15 years, with around 3-5 years more common for nets and ropes. In some cases redundant equipment may be re-used, for instance smaller cages, now uneconomic for salmon, are ideal for the start-up of the cod industry. Landbased units using reinforced concrete structures can be demolished and the metal separated for recycling and the concrete rubble used as ballast in other building projects.

The manufacture of feed requires substantial feed plant machinery, its delivery requires trucks, fuel, and road maintenance, and there can be disposal issues linked with packing materials. For instance much feed is still supplied in 25 Kg plastic bags, which cannot be reused due to disease transfer risks, and has traditionally gone to landfill. At least one recycling firm is now addressing this issue and companies are also investing in bulk delivery solutions.

2.3 Management of feeding and nutrition

Pond-based aquaculture in many countries is based on stimulating natural food production through the addition of inorganic and organic fertilisers. By contrast, most European mariculture relies on the use of fully formulated diets to elevate production well above what would normally be ecologically sustainable within a given water volume. This raises two key issues, firstly the formulation of feeds and the sourcing of materials for them. The second is the fate of the waste that is produced as a result of feeding the fish.

2.3.1 Feed formulation

Formulated diets are expected to provide the best growth rates, economic performance, flesh quality, and lowest possible environmental impact. Formulators need to consider the digestibility of diets (to minimise waste), the protein to energy ratio, physical qualities such as pellet hardness, stability, sinking rate etc., vitamin and mineral levels, and nutrient availability including essential amino acids and lipids. The needs of different species and life stages vary significantly. Feed ingredients are increasingly regulated in Europe, for instance with the removal of bovine material from fish diets, or new limits on PCB and dioxin contaminants. Ingredient costs may also vary considerably due to fluctuations in supply and demand.

Most aquaculture diets, especially those used in salmon farming, are based on fishmeal and fish oil, as these have the most suitable nutritional profiles and best digestibility. However, there are resource issues as approximately five tonnes of fish are required to make one tonne of fishmeal. Commercial salmon diets are composed of about 45% fishmeal and 25% fish oil and thus it takes around 2.8 tonnes of wild caught fish to produce one tonne of salmon. Although such intensive aquaculture practices are net users of fish (Naylor *et al*, 1998), it may also be viewed as a value adding process, converting unattractive fish for human consumption into much higher valued food product. The more critical issue is that if aquaculture is to expand further along current lines, the demand for fishmeal and fish oil will continue to rise. As supplies are already considered to be at sustainable limits this leads to fears that aquaculture will encourage unsustainable resource exploitation. The International Fishmeal & Fish Oil Organisation (IFFO) point out that fishmeal and oil production has not increased as a result of aquaculture demand. Rather, aquaculture has taken an increasing share of the available resource. Their forward projections suggest the use of fishmeal by aquaculture will rise from 34% in 2002 to 48% in 2010, with other livestock taking a smaller share. The issue of fish oil is more critical with aquaculture already using 56% of supplies in 2002, and potentially requiring 79% of supplies by 2010. Research is therefore examining the scope and candidates for fish oil substitution, with early results proving encouraging. Indeed, commercial diets have already substituted some of the fish oil for vegetable oils. This lowers the content of beneficial omega 3 fatty acids in the fish flesh, but also helps reduce levels of dioxins and PCBs in aquaculture feeds. Overall therefore, this is likely to be an acceptable trade-off to both the industry and consumers. Some substitution of fishmeal by vegetable proteins is already practiced, but growth rates fall and digestibility decreases as inclusion levels rise. The result is that the fish produce more faeces with potentially greater release of carbon and to some extent nitrogen and phosphorus into the environment in open systems. Genetic engineering may offer a number of solutions to these constraints, although another alternative is marine zooplankton as a source of feed protein and lipids. Research is underway in Norway[5] to investigate the feasibility of harvesting marine zooplankton for use in aquafeeds. This is still at a very early stage and not yet proven either technically or economically, but is of interest due to the higher biomass of the resource (estimated at 90 million tonnes for the Norwegian sea alone). However, even without these more speculative technologies, the continued growth of aquaculture within current resource constraints appears possible well beyond the ten-year horizon.

5 Norwegian University of Science and Technology, CALANUS programme.

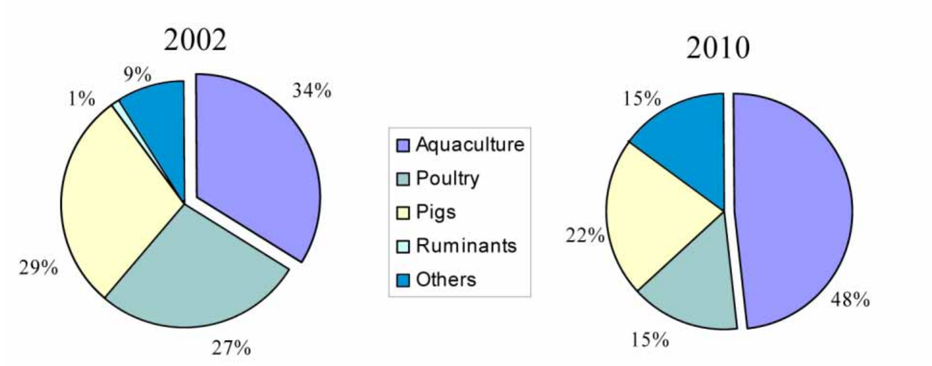

Figure 2.5: IFFO data and projections for fishmeal utilisation 2002-2010

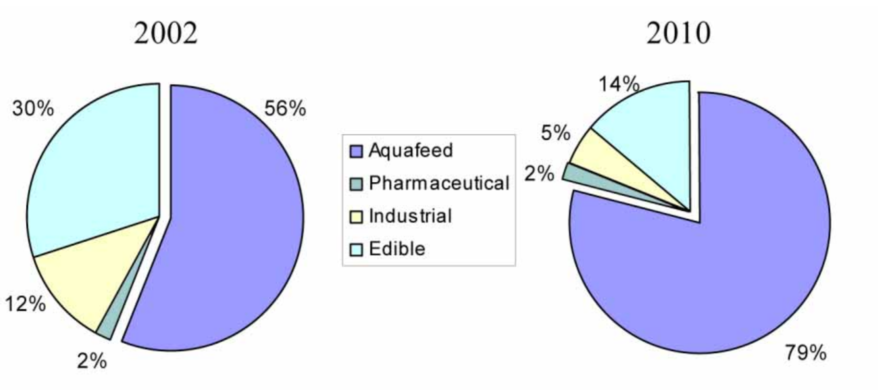

Figure 2.6: IFFO data and projections for fish oil utilisation 2002-2010

The inclusion of carotenoid pigments, astaxanthin and canthaxanthin in some aquaculture diets has been questioned on human health grounds, but also with respect to discharges to the environment. In the aquatic environment, astaxanthin is biosysnthesised by microalgae or phytoplankton and passed up the food chain. The use of astaxanthin and canthaxanthin in compounded diets therefore mirrors the diet of wild fish and provides colour and anti-oxidant properties. These pigments are considered more than simply "cosmetic colourants". As antioxidants they protect against effects of oxygen-free radicals and may be seen as important to good fish health, and thus an essential dietary component, although the inclusion level used in salmon and trout is mainly determined by market requirements for well-coloured flesh. Most of the astaxanthin and canthaxanthin in use is manufactured by means of a chemical process, although some natural sources are available. As a component of aquaculture waste (uneaten feed and faeces), it is deposited in the sediment beneath fish cages, and is relatively resistant to anaerobic degradation. Their environmental impact is considered to be benign, but is little researched.

2.3.2 Management of feeding

In intensive aquaculture, waste outputs can be related directly to feed inputs. These wastes are in the form of solids, through uneaten food and faecal material, and soluble forms which are the products of metabolic activity, such as ammonia and urine, and carbon dioxide. Intensive aquaculture in ponds and land-based enclosed systems can contain and treat wastes before discharge but cage based aquaculture, i.e. marine or lake- based fish farming, is ecologically open to the wider environment. Thus nutrients may freely enter aquatic systems.

Impacts on water quality

Excretory products form cages are largely dispersed in the water column by currents while solids tend to fall to the sea or lake bottom. The latter may be consumed by indigenous animals (Carss, 1990) or broken down to finer particles. Nutrients are solubilized and quantities released depending on the physical environment (Phillips *et al*, 1993) or released from sedimented solids (Kelly, 1992), with as much as 60% of the total phosphorus and 80% of the total nitrogen ending up in the water column (Hall *et al*, 1992). At marine sites, where dilution is much more rapid, effects are transitory. However, hypernutrification can occur at freshwater cage sites where currents are low and where dilution is limited (Costa-Pierce, 1996).

Impacts on sediments

Solid nutrients become largely incorporated into sediment near to the aquaculture cages, though amounts are dependent on the physical environment, the culture method and the species being grown. Effects of solids loadings are apparent at many marine and freshwater sites, with faecal and food wastes from intensive cage farming causing elevated levels of organic carbon, nitrogen and phosphorus in adjacent sediments. This in turn stimulates microbial production, changing sediment chemistry, structure and function. The oxygen demand increases and sediments become increasingly anaerobic and reduced[6], and there is an increase in the evolution of nitrogen and phosphorus compounds into the water column. In marine environments methane and hydrogen sulphide are produced in sediments, which under extreme conditions will be released.

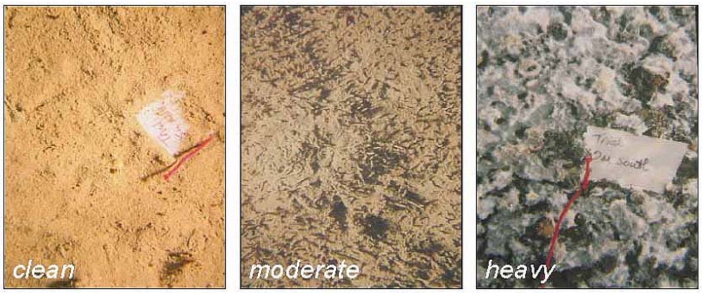

Figure 2.7: Sediment accumulation below fish cages

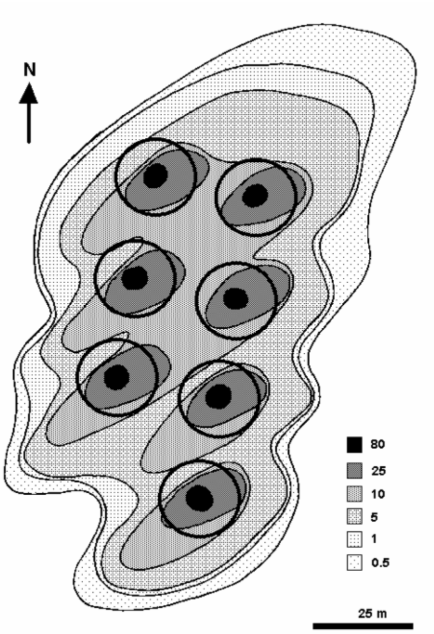

Figure 2.8: Dispersion of sediments beneath cage, depending on prevailing current direction and velocity. The black circles show the cage positions and the contour map the carbon loading.

6 Reduced sediments donate electrons in chemical reactions, as opposed to oxidizing sediments that accept electrons. The tendency for the sediment to be oxidizing or reducing is determined by measuring the REDOX potential.

The impacts on the sediment function and chemistry can lead to changes in the animals inhabiting them. Heavily impacted sediments are often dominated by tolerant species such as oligochaete or capitellid (blood) worms, while less tolerant species disappear from near the fish cages (Gowen *et al*, 1991). Occasionally, there may be an azoic zone devoid of oxygen, where sulphur bacteria (*Beggiatoa* sp.) occurs. These sediments may take up to 10 years to recover, though most recovery takes place within 2 years of cessation of fish production (Nickell *et al*., 1998). In pond culture, similar conditions may occur within sediments leading to acid volatile soils. These are periodically cleared but disposal of these toxic sediments is often a problem. In addition, at cessation of aquaculture these areas may not be used for other activities, such as to grow crops for some considerable time.

Technical solutions

Technology solutions to preventing the discharge of wastes have been tried and are discussed further in Section 4.1, however, these are not currently feasible for most sites. Much greater progress has been made with feed management systems that aim to optimise feed intake and minimise waste (also covered in 4.1). This starts with the digestibility of the diet itself, and the ability of the fish to convert the feed to flesh (possibilities for improvement through selective breeding). Feed conversion can also be enhanced in salmon through the use of artificial lights to extend day length, and the use of additional aeration or oxygenation devices where oxygen supplies becomes limiting. Even distribution of the feed to the fish stock is important to prevent dominant fish overfeeding and weaker fish being underfed. Fish also have natural diurnal feed patterns, which vary with season and fish size, but which can also be affected by environmental conditions, stress and health factors. The optimal matching of feed supply with demand is therefore complex, and current technical solutions focus on providing accurate feedback on fish feeding activity to prevent feed being supplied if it is not being consumed by the fish. The more sophisticated control systems also incorporate fish feeding models to help optimise delivery patterns and to ensure that feeding above or below expected levels can be investigated and production properly planned. For this it is essential to have accurate data about the number and weight distribution of the stock and suitable growth and feed models. A variety of systems are available to help monitor fish size and numbers, involving optical sensors, sonar and stereo video technology, although high cost and limits to accuracy deter universal adoption. Future technologies should improve the number and varieties of monitoring systems, improve feed delivery patterns and use more intelligent control systems.

Shellfish

Shellfish farming (excluding hatcheries) utilise natural feed, so are usually considered more environmentally benign. However, they feed by filtering microalgae and other organic particulate material from the water, hence diverting nutrients from other aquatic food chains. For instance, up to 30% of nitrogen originally incorporated in the phytoplankton can be deposited to sediments (Carver & Mallet 1990). The deposition of waste solids (pseudofaeces) below suspended shellfish culture sites can be considerable, and increase the organic content of sediments. As animals they also remove oxygen from the water, produce carbon dioxide and excrete ammonia. Where this is considered to be an issue, solutions are being sought through wider environmental management, rather than engineered technologies.

2.3.3 Marine hatcheries

Marine fish hatcheries use limited amounts of formulated feed for broodstock and fry weaning. The main distinguishing feature of both marine fish and shellfish hatcheries are that they tend to rely heavily on live feeds. These are mainly species of marine microalgae (phytoplankton), zooplankton (rotifers and copepods) and *Artemia* (brine shrimp). Microalgae are usually cultured on-site using pure starter cultures grown on in plastic bags, cylinders or tanks provided with inorganic nutrients, carbon dioxide and illuminated by sunlight or fluorescent lamps. Rotifers and copepods are similarly cultured on-site using microalgae and liquid nutrient & lipid enrichment media in well aerated tanks. *Artemia* are purchased as encysted eggs from international suppliers (the majority harvested from the Great Salt Lake in Utah, USA), which are then hatched as required and enriched in the same way as rotifers. Freeze dried microalgae and zooplankton are sometimes used, as are microencapsulated artificial diets. However, these are rarely as effective as live feed.

Few significant environmental issues are associated with the use of live feeds. The volumes of nutrients used and quantity of waste produced is very low and therefore unlikely to be a major input into the environment. *Artemia* production is somewhat variable, but the major sources are managed for sustainability. The species used tend to have very wide distribution, so translocation of non-native species is rarely a major concern. The potential for live-feeds to act as a carrier for fish and shrimp diseases has been investigated, but not yet substantiated as a significant risk.

The production of live feed is costly in terms of labour, equipment, space and energy usage. Artificial diets remain the long-term goal. However, phytoplankton and zooplankton may also be aquaculture products in their own right. Phytoplankton are a potential source of a wide variety of compounds of nutritional, biochemical and pharmacological interest, including lipids, pigments, biocides, polysaccharides, anaesthetics, biotoxins, anti-inflammatories etc.

2.4 Management of reproduction and stock genetics

2.4.1 Closing the reproductive cycle

A reliable supply of good quality "seed" is essential for consistent aquaculture production. Some species are produced whilst retaining a reliance on natural breeding. Often this is due to technical constraints (e.g. eels, many reef fish, tuna and certain shrimp), but may also be economic (e.g. mussels). This situation is often unsatisfactory for producers and raises concerns over the environmental and ecological impact of exploiting natural populations for aquaculture. For other species, hatchery technology is well developed, or is at least sufficiently developed to allow commercial activity.

Table: 2.4: Status of hatchery technology

Status of hatchery development	Example species
Hatchery technology relatively straightforward with good survival rates – in widespread use	Salmon, trout, tilapia, carp, catfish and many other species of freshwater fish
Hatchery technology more complex with modest survival rates or other constraints but commercially viable and well established	Sea bream, sea bass (European and Asian), turbot, shrimp
Hatchery technology more complex with low survival rates or other constraints, low numbers of commercial units to date	Halibut, Grouper, Cod, Haddock, and many other species of marine fish
Hatchery technology still experimental or	Tuna, eel and many other marine species

The process of closing the reproductive cycle firstly requires the parents to be brought to full sexual maturity possessing high quality gametes (eggs and sperm). This involves providing good nutrition, health and environmental conditions. Secondly they must be encouraged to spawn, possibly through the provision of an environmental stimulus (change in temperature, increase in water flow, or provision of a suitable spawning substrate etc), or alternatively with the assistance of hormone treatments. Thirdly the eggs need suitable conditions to maximise survival through to hatching. Fourthly the hatched larvae require suitable conditions and a well-managed introduction to external feeding. Fifthly, the transition to fry (in the case of fish) needs to be managed to minimise cannibalism and ensure successful weaning onto artificial diets. The survival rate of many wild marine species from egg to adult is below 1%, and during the larval stage mortality rates are commonly between 5 and 10% per day. Hatcheries need to substantially improve on these survival rates in order to be financially viable.

Environmental issues associated with hatcheries are broadly similar to later stages, but much reduced in scale due to the lower biomass involved. The relatively high unit value of the hatchery product also means this sector is able to use more sophisticated tank and water treatment technologies, further reducing direct environmental impacts. Any remaining impacts should also be evaluated in relation to the benefit of reducing exploitation of wild stocks. Future technology developments will involve extending the range of species that can be raised in hatcheries, improving survival rates and perhaps increasing the use of artificial diets.

2.4.2 Achieving consistent year-round production

One of the targets of modern food-sector retailing is consistency of supply, with consequent demands on producers for regular year-round production of consistent size and quality product. This is a major challenge for species such as salmon, which have a seasonal production cycle. As with fruit and vegetables, there is sometimes an option for buyers to purchase directly from both north and south hemisphere producers. However, various technical solutions are also employed to minimise this constraint. Firstly, environmental controls can be applied to encourage broodstock to reproduce out of season. For temperate species fish this normally involves manipulating the photoperiod (the duration of light as opposed to dark experienced by the fish each day). Depending on the species, breeding may be stimulated by decreasing or increasing day length. Some control over temperature may also be used, although is not generally such a critical factor. By advancing the photoperiod cycle for some broodstock and delaying it for others, the normal period for breeding can be extended, providing greater flexibility for growout to meet market requirements. Secondly, as fish are cold-blooded animals, the growth rate is influenced by water temperature. In controlled hatchery conditions it is sometimes possible to advance or delay batch growth rates by adjusting the temperature above or below ambient conditions. With salmon, which reproduce and undergo early development in freshwater, manipulation of the smolting process (where the fish become ready for life in seawater) is also possible through the use of photoperiod controls. More recently, a US company (MariCal) has introduced a further approach based on stimulation of the osmoregulatory control system within the fish through the addition of magnesium and calcium ions to the water and the inclusion of salt in the diet. Improved understanding of fish biology in the future may lead to further approaches becoming available. For the present there are no specific environmental impacts associated with these techniques, although the reduction in seasonality in production processes suggests an altered pattern of outputs, which might have both environmental benefits and drawbacks.

2.4.3 Improving and optimising stock for aquaculture

There is a long history of animal domestication and crop improvement programmes in agriculture, aimed at improving production efficiency, resistance to disease, and enhancing other desirable characteristics. These objectives are shared by aquaculture, with environmental drivers also playing a part in domestication research. For instance improved conversion of feed into fish flesh reduces waste output; modification of dietary requirements could ease the pressure for fishmeal and oil; improved resistance to diseases could reduce the need for chemical therapeutants. There are two main approaches to this. Firstly domestication through traditional selective breeding, but using the modern tools of molecular biology to help plan, monitor and manage the programme. Secondly, the use of transgenesis to introduce new DNA into the genome. For various species it has also proved desirable to produce single-sex and/or sterile stock, e.g. if the growth rate of one sex is far superior to the other, and if reproductive maturity is normally reached before the fish reach market size. Sex reversal and sterility have been best achieved through the use of chromosome set manipulations.

Selective breeding programmes

Nearly every other farm animal and plant has undergone radical genetic improvement compared to it wild progenitor. Genetically, the stocks used in marine aquaculture are virtually wild. This is partly because aquaculture is a new industry with many other pressing problems and partly because of the difficulties in undertaking scientifically sound improvement programmes because of the biological limitations imposed by these species. The evidence is that in many farmed populations of fish in which the life cycle has been closed the stocks are being genetically degraded though inbreeding and genetic drift. These problems accumulate in small populations of animals, particularly, as in the case of many farmed fish species, if there is no attempt to manage the replacement of the stock. Inbreeding and genetic drift reduce the commercial viability of the stock by reducing genetic variation that lowers viability and any possibility of future selective improvement. A number of scientifically sound genetic improvement programmes are now being developed which assess the genetic variation present in the wild so that the best wild strains are used as the basis for the farm stock. Norwegian strains of salmon were identified has having the best overall characteristics of all the strains tested and now widely used in Scotland, Ireland and Chile. These selective breeding programmes utilise a classical quantitative genetic approach but have to incorporate specialised facilities to maintain the families produced each generation in isolation until the young are large enough to be physically tagged. Today these are usually Passive Integrated Transponders (PIT tags) inserted into the fish when they grow to about 10g. Recently developments in DNA fingerprinting are now being incorporated into these programmes to identify the pedigree of individual fish in large untagged commercial populations. If all the parents are fingerprinted then it is possible to accurately predict the fingerprint of the offspring from any given set of parents. These genetic markers greatly increase the flexibility of existing selective breeding programmes and for the first time will enable scientifically based programmes to be developed in mass spawning marine species in which it is impossible to know the pedigree of any individual fish in the past. The application of these techniques has dramatically improved the potential rate of genetic gain in established programmes and reduced the potential cost and increased the flexibility of the design of improvement programmes in new species. Such programmes are helping to improve growth rates and disease resistance with indicative gains of 10-15% per generation in several different farmed fish. Parallels are often drawn with the poultry industry, where growth rates and laying potential have increased by 300% in the last 30 years through selective breeding. The high fecundity and higher innate levels of genetic variation make the potential genetic improvements in aquatic species enormous. Selective improvement of farmed fish should increase the efficiency of aquaculture as the animals will be better adapted to the farm environment so they will grow quicker be less stressed and more disease resistant and utilise less food than the wild fish. This should help to reduce the direct environment impact of aquaculture but they might pose more of a threat to wild populations of the same species. (see discussion on biological containment, Section 2.2.3)

Transgenesis

Genetic modification, through the introduction of DNA into the genome - transgenesis - is relatively well established as an experimental technique in many fish species, due to the ease with which fertilised eggs can be manipulated. Various fish and human growth hormone genes have been incorporated in the genome of species such as Pacific salmon, rainbow trout, common carp and tilapia. The most publicised promoter of these technologies is Aqua Bounty, a North American company involved in the commercial development of transgenic Atlantic salmon. This company uses only fish genes in the DNA injected into eggs they hope will become integrated into the genome of the species they are trying to change. A number of genes that encode for growth promoting hormones (e.g chinook salmon growth hormone gene) along with promotor genes such as the antifreeze protein gene promoter from the ocean pout that allows the gene to be activated have been introduced into a number of species. Where these genes have been successfully integrated into the genome of the recipient then between three to five-fold increase in growth rate has been reported, with some individual fish being 10- to 30-times larger in the early phase of growth. This early work was done on wild stocks, but subsequent work using domesticated strains selected for growth rate the gains are much lower. However, it must be remembered that this is a one-off improvement of a single trait and it will take several generations of breeding to develop commercial lines from the original single transgenic animal. This does not compare well with the continuous improvement and performance monitoring that accompanies a classical selective breeding approach that can improve a strain at several different traits at the same time. These technologies have some promise for the improvement of traits such as disease resistance, which are more difficult to improve through selective breeding. Fish are also generally unable to utilize carbohydrates, or terrestrial protein and oil sources. This may be a particular limitation in the future especially given the finite supply of natural fish oil. The use of transgenic techniques to either change the fish to cope with these novel materials or to change the plant to make its nutrients more available to fish is being actively pursued. GM approaches may also be taken to improving disease resistance.

Despite early promise, practical problems with transgenesis have been encountered and are being actively researched. These include the fact that most injected animals (G0) [7] or transgenes are mosaic, i.e. the inserted genes are not equally expressed in all cells and tissues, so it is important to confirm that they can pass on the gene in their gametes. At present the technology is serendipitous in that the numbers of gene copies and where they insert themselves in the whole genome is random. Each individual is therefore unique and the effect of the insert on subsequent performance equally so. While much is made of the potential environmental disadvantages of GM stocks, there is no clear evidence on the potential biological impact of GM escapees capable of breeding in the wild, existing impact studies being based on laboratory analysis of ornamental species, or on modelled scenarios for escaped population. Given the need to establish adequate precautionary approaches, unless reared in highly secure land based systems, such GM fish would almost certainly need to be sterile, (though as with non-GM stocks large numbers of escapees could still compete for resources with wild fish stocks and interfere with successful spawning). With no evidence to date of any food safety issues, and apparently good potential financial benefits to the use of GM fish, research and development is likely to continue, and applications for marketing authorisation are already with the US Food and Drug Administration (FDA), though state-level approvals, with the exception of Maryland, are so far negative. With the high level of public concern over GM technology, rapid uptake in Europe appears unlikely, even when fully licensed. However, this may change over the 10-30 year time horizon if the commercial rationale, and price advantages are compelling, consumer acceptance improved and ecological safeguards fully developed. In particular, recent developments of 'auto-transgenics', where genetic materials are introduced only from the same species, may offer a greater level of acceptance.

Chromosome set manipulations and hormone treatments

Aquatic organisms being cold blooded are greatly affected by the environment in which they are reared. A range of physical, chemical and environmental factors can radically change the eventual phenotype of any given individual. A range of shocks such as temperature and pressure can influence the number of chromosome sets eventually present in a developing zygote. Although these changes can occur in nature they are rare, but the frequency of these events and the unique individuals produced can be increased under controlled conditions. Chromosomal set manipulations rather than genetic manipulations are used in some branches of aquaculture. Triploid fish, having three sets of chromosomes (rather than the usual two), are easily produced by shocking the newly fertilised eggs with heat or pressure. Triploidy is not a genetic modification and does not interfere with the normal growth of these individuals but does disrupt gonad development at the second meiotic development so they are unable to produce viable gametes. This technique can used to stop gonad development in species in which maturation occurs prior to the animal reaching a commercial size (oysters or production of large rainbow trout). It can also be used to

7 First generation stocks whose genetic material has been directly modified

produce sterile offspring to reduce the risk of an exotic farmed fish escaping and becoming established in the wild or to stop farmed strains interbreeding with wild populations of the same species. This technique is easy to apply by farmers and is used commercially all over the world. Sterile fish could be seen as route to reduce the genetic impact of farm escapees and has been tried in Atlantic salmon. However problems with the hardiness of triploid salmon meant that farmers quickly reverted to the use of normal stocks. The majority of the problems seem to be related to the larger cell size of triploid animals which cause problems in nutrient and gas exchange across membranes making the animals more prone to stressors such as low oxygen or handing.

Production of single sex populations of farmed fish is routine in a number of species (e.g. all-male tilapia and all female rainbow trout), where there are significant differences in growth performance between males and females. This is most easily achieved by treating first feeding fry with a steroid hormone to produce a population that is functionally single-sex, but genetically mixed. However, as the use of hormones in fish intended for human consumption is restricted in many countries, alternative techniques that treat the parent fish, allow the production of genetically single-sex populations that have not been hormone treated. The more advanced techniques include gynogenesis and androgenesis, which produce normal diploid offspring, but using only genetic material from the female or male parent respectively. Chromosomal manipulations have also been developed for a range of commercially reared tropical marine fish species, the application of which, unique to aquatic organisms, will undoubtedly help to speed up the development and improvement of marine species as it has in other farmed fish.

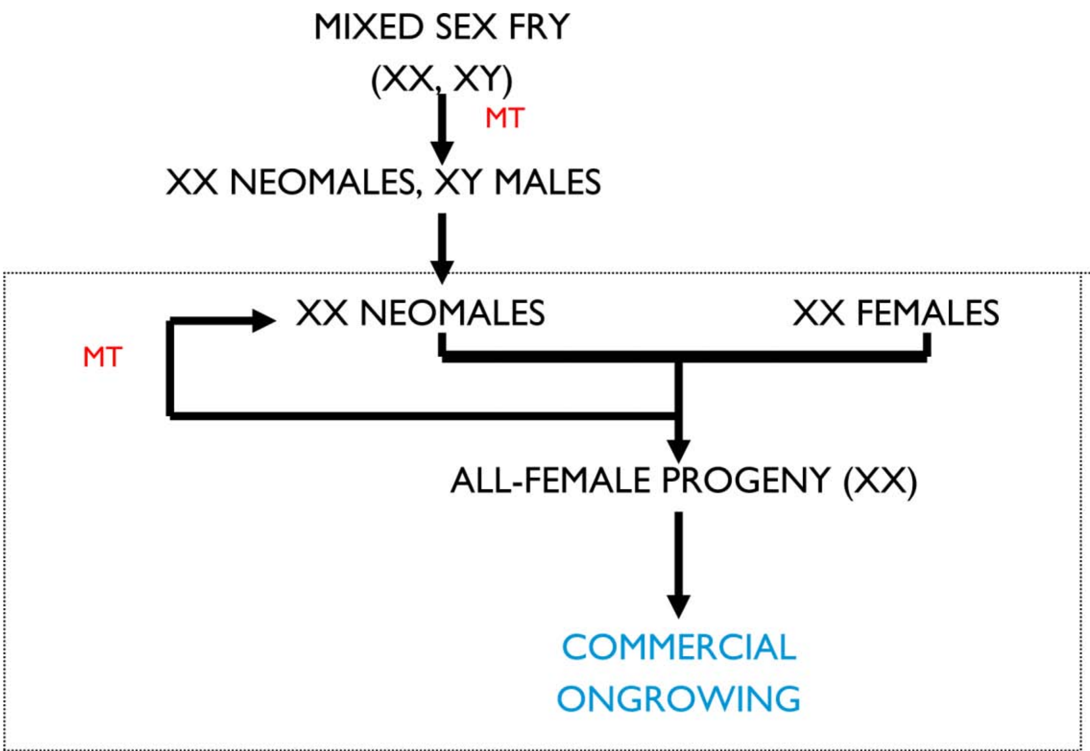

Figure 2.9: Breeding programme for the production of all-female rainbow trout. Boxed area indicates commercial production cycle. MT = 17-alpha methyltestosterone; XX neomale = genetically female XX fish which has been hormonally masculinised to phenotypic male. After Bye and Lincoln (1986).

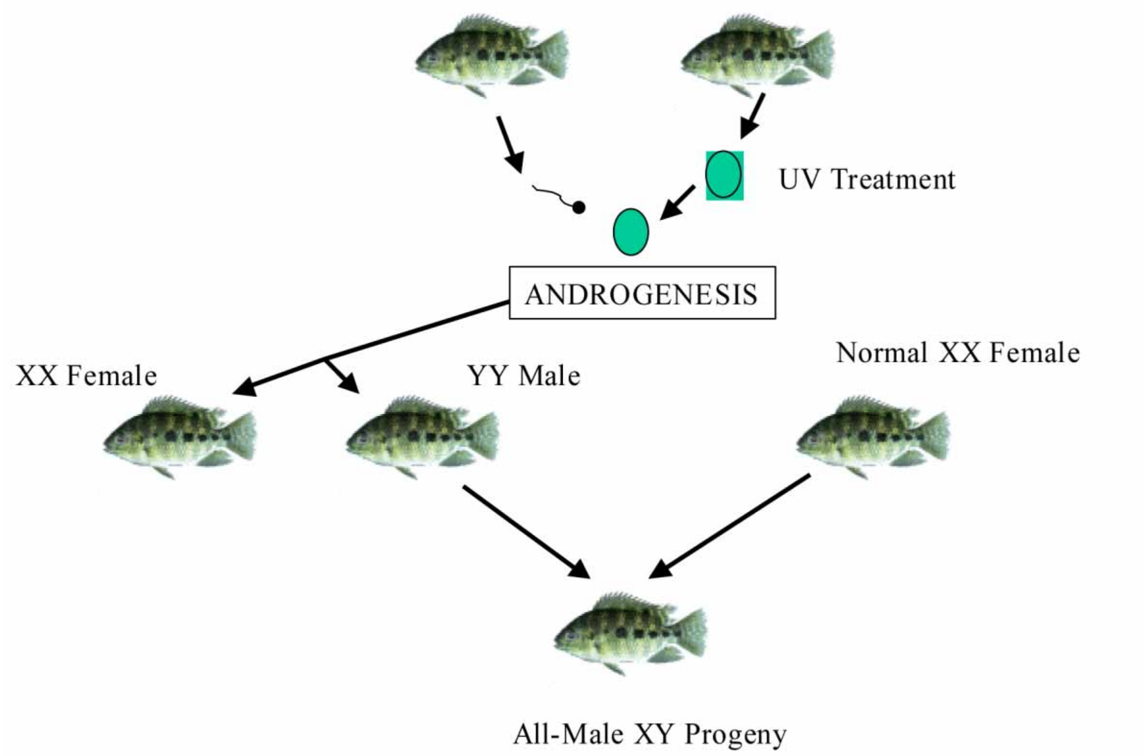

Figure 2.10: Method of producing all-male tilapia using androgenesis

2.5 Health management

2.5.1 Overall objectives and management approaches

The maintenance of healthy stock is one of the primary objectives of every aquaculture manager. Disease problems can quickly lead to mortalities, poor performance and economic loss. The proximity of large numbers of individuals is inevitably a problem if there is an infectious disease outbreak, and environmental contact with wild populations adds further difficulties. Basic management procedures aimed at preventing the outbreak of disease include:

- Avoidance of stress factors that are known to increase the risk of disease, for instance poor water quality, poor nutrition, overstocking, excessive handling or disturbance etc. (i.e. promotion of good welfare)
- Separation of stocks as far as is possible, and in particular, separation of different generations, so that adult carriers of disease do not immediately infect juveniles
- Regular disinfection or fallowing of facilities, especially between batches. Also regular disinfection of equipment, protective clothing and vehicles etc. to prevent any transfer between sites or units.
- Regular monitoring for disease problems with the aim of identifying and treating before a serious outbreak occurs (sometimes involving coordination between several farms)
- The use of vaccines and immunostimulants, to boost immunity to diseases, and where appropriate, prophylactic treatments to prevent infection.

Once a disease outbreak occurs, there is a limited range of (mainly licensed) medicines available for treatment (the actual list varies from country to country). These are commonly administered either by inclusion in the feed, or diluted in the water as a bath treatment. For water-based aquaculture, or flow-through land-based systems with little or no effluent treatment, preventing the discharge of therapeutants into the environment can be very difficult. The environmental impact (if any) from such discharges is clearly related to the nature of the specific compound and the scale of use.

2.5.2 Interactions with wild stock

Diseases can be transferred between wild and farmed fish wherever there is a shared environment. Most disease problems in aquaculture start as infections entering the farm from wild sources (e.g. via untreated water supplies from rivers, lakes and the sea). However, farmed stock can also be carriers of a disease, infecting other farmed and wild stock as they are moved from one location to another. More significantly, fish farms that are open to the environment may act as reservoirs for disease agents, thereby increasing overall infection levels in the wild (this applies to shellfish as well as fin fish). The most researched example of this is the effect of salmon farms on sealice infections on sea trout. Bjorn *et al* (2001) found that sea trout populations feeding in areas where farmed salmon are common have higher infection than those in other areas, with up to 47% of the wild fish, in the most severely infected areas, having a lice burden shown to induce mortality in laboratory experiments. However, they appear to return to the rivers (freshwaters) earlier, where sealice cannot survive, hence improving chances of survival and reproductive success. More recent, anecdotal data shows that there is considerably less lice infection on farmed fish than previous, for example there has been a significant improvement over the past year in Scotland, with the introduction of an effective targeted treatment against sealice. This in consequence has reduced the environmental loading of the larval stages (unpublished, Industry data). The principle of this concern may extend to other species and disease agents, suggesting continued vigilance will be required.

2.5.3 Use of vaccines

A limited range of vaccines are currently available to aquaculture. The most successful have been those against gram negative bacteria, although there are a limited number of products for gram positive bacteria and some viral diseases. Vaccines against parasites are under research, but so far there are no commercial products available. Vaccines are administered as a bath treatment, e.g. in the hatchery, orally (with feed), or by injection. The latter is the least favoured but currently most effective. The duration of immunity is limited, and booster vaccinations are sometimes required. It appears the specific immune response in fish is not well developed until they are at least a gram in weight. Shrimp never appear to develop a specific immune system. For these groups, and for providing additional protection for larger fish, immunostimulants are available that boost the non-specific defence mechanisms. A variety of compounds are used, perhaps most commonly beta-glucans derived from yeast, although others are under development.

There have been few environmental concerns raised in connection with the use of vaccines and clear environmental benefits where they reduce or eliminate the need to use therapeutants and other treatment chemicals. There are potential issues with the use of live (attenuated) vaccines including the spread of vaccinated strain to non-target species, possibility of reversion to virulence or the genetic reassortment of strains. However, for these reasons there are no live vaccines authorised for use in the UK. The use of thimerosal, a mercury-based preservative, in some human multi-dose vaccines has been another issue of concern. It is permitted for use in fish vaccines under EC Regulation 2377/90 (Annex II) providing the concentration does not exceed 0.02%. However, it is not known to be used in any commercial fish vaccines in the UK. As the number of fish to be vaccinated is usually very large, multi-dose batches are expected to be used immediately and preservatives are not considered necessary. Another compound that can be used as a preservative is formaldehyde, but more commonly it is used as an inactivating agent in earlier generation vaccines. This is also permitted in Annex II of EEC 2377/90 with a limit of 0.5 g/l (0.05%) set by the veterinary Medicines Directorate (VMD), unless higher concentrations can be shown to be safe. Another ingredient of many fish vaccines is an adjuvant, which enhances the immunogenicity of the antigen. The use of mineral oils as adjuvants is decreasing due to known side-effects and potential risks (e.g. to vaccinators if accidentally self-injected). Some current vaccines contain aluminium hydroxide or glucans as adjuvants. Oral and immersion vaccines have used Potassium aluminium sulphate or dimethyl sulphoxide (permitted under Annex II of EEC 2377/90). It is worth noting that as with other veterinary products, market authorisation requires both safety and ecotoxicity studies to be carried out. Where there is any possibility of vaccine residues remaining in the fish flesh, a suitable withdrawal period is established (see Directive 2001/82/EC).

Vaccine development is at the leading edge of biotechnology and several new approaches are under serious development or trial. These include the use of recombinant DNA technology for vaccine and adjuvant production and more revolutionary, vaccines based on direct injection of DNA into the muscle, the cells of which take up the DNA and produce antigenic proteins over a longer period, directly stimulating the immune system. Overall this is an area where substantial (and welcome) progress may be made, but continuing vigilance required to minimise the risk of any unknown environmental impacts occurring.

2.5.4 In-feed treatments

Historically, the most common in-feed treatments were antibiotics, used against a range of bacterial diseases. However, due to improved vaccines and husbandry, usage has fallen dramatically, especially in the salmon industry (Table 2.5), where in-feed antiparasitics are now more significant.

Antibiotics

In more open aquaculture systems, a significant proportion of the administered therapeutant may be discharged to the environment in association with uneaten food and faeces. Some of the antibiotic leaches into the water and is quickly broken down, posing little problem (Weston, 1996). However, most reaches the sediments where it can persist for many months after treatment (Weston, 1996). While the bioavailability of antibiotics in sediments are limited, they may lead to an impact on sediment degradation processes and chemistry (Beveridge, 1996). High levels of antibiotics, such as oxolinic acid, have been detected in wild fish, crabs and mussels several hundred metres from salmon farms (Samuelson *et al*, 1992). Use has decreased considerably in fish farming with the introduction of vaccines against major diseases (Beveridge, 1996). Many studies have reported an increase in the resistance of pathogens due to use of antibiotics in aquaculture (Kerry *et al*, 1994), though the implications of this data is difficult to assess until more is known about the long term environmental fate of these chemicals in the sediments.

Table 2.5. The consumption (kg active compound) of in-feed treatments in Norwegian aquaculture from 1990 to 2000

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Antibacterials											
florfenicol	0	0	0	56	14	64	64	123	135	65	146
flumequine	1 959	3 837	9 833	2 177	227	182	105	74	53	7	17
furazolidone	118	131	0	78	0	0	0	0	0	0	0
oxolinic acid	27 659	11 400	7 687	2 554	811	2 800	841	507	436	494	434
oxytetracycline	6 257	5 751	4 113	583	341	70	27	42	55	25	2
sulfadiazine/ trimethoprim	1 439	5 679	5 852	696	3	0	0	0	0	0	0
Antiparasitics											
diflubenzuron	0	0	0	0	0	0	160	361	437	50	12
teflubenzuron	0	0	0	0	0	0	610	1 510	1 334	231	62
emamectin	0	0	0	0	0	0	0	0	0	4	34
praziquantel	177	188	86	79	119	110	130	225	195	239	100
fenbendazole	60	56	10	2	2	0	0	15	16	12	39

Source: Norwegian Medicines Directorate/Statistics Norway 2002

Antiparasitics

A number of anti-parasitics are also administered as in-feed treatments. These include very limited use of antihelminth drugs (e.g. praziquantel and fenbendazole) and growing use of new anti-sea lice drugs, primarily the avermectin, emamectin benzoate (SLICE™), and the acylurea, teflubenzuron (Calicide™). Again, these tend to be incorporated into sediments through uneaten food and faecal material. Little is known of their bioavailability to sediment organisms but they show some potential for persistence, though in quantities below current environmental quality standards of impact. There is considerable investigation being undertaken at present on the environmental impacts of these chemicals on sediments and water column in the vicinity of aquaculture systems. Additionally, computer-based models of environmental dispersion of infeed treatments are under development and already enable more effective environmental management and regulation for these medicants (SEPA, 2002).

It is anticipated that future generations of drugs will be more specific in their actions and therefore have lower risk of affecting non-target organisms. The efficiency of uptake may also be improved so that discharge to the environment is much reduced.

2.5.5 Bath treatments

Bath treatments generally involve the addition of a chemical to the water in which the fish are held and the concentration maintained for a specified period of time (from a few minutes to several hours). They are most commonly used against external parasites and fungal infections. Treatments range from common salt through formalin to antimicrobials and pesticides. Such treatments are especially common in hatcheries, but can also be necessary in grow-out facilities. Treatment in cages is achieved by reducing the volume of the net (by lifting it to approximately 3 m deep) and surrounding it with a tarpaulin. The treatment is then administered, and after the required period, the tarpaulin is removed and the net dropped to full depth, allowing the chemical to be flushed away. Tanks may similarly be treated by reducing water volume and shutting the inlet and outlet before adding the treatment chemical. At the end of the treatment, the water supply is reinstated and the chemical is flushed from the tank. For both tanks and cages it is usually necessary to provide temporary oxygenation to avoid anoxia during the treatment.

The most commonly used bath treatment against disease in the marine environment are parasiticides. In particular the highest profile in terms of potential for environment effect are those against sea-lice. Although the use of in-feed treatment is growing, bath treatments remain an important second line of defence, especially considering the potential for resistance to treatments to develop. Available treatments include hydrogen peroxide, pyrethroids and organophosphates as active ingredients. While the former is thought to be non-impacting it is cumbersome to use and not popular. The pyrethroids and organophosphate treatments are more popular but are released directly into the environment after the treatment period. These are usually diluted within a very short time period, though the impacts on the pelagic ecosystem is largely unknown and under investigation (Medina *et al*, 2002). Pyrethroids in particular tend to bind strongly to organic material within the environment and, whilst not bioavailable in that form, may have the ability to be more persistent than laboratory experiments suggest.

Table 2.6. The use (kg active ingredient) of bath treatments in Norwegian aquaculture from 1990 to 2000

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Antiparasitics											
metriphonate	2 408	2 144	1 946	1 779	1 227	281	138	0	0	0	0
dichlorvos	3 416	3 588	3 155	2 470	1 147	395	161	36	0	0	0
azamethiphos	0	0	0	0	389	738	606	315	182	14	0
cypermethrin	0	0	0	0	0	0	23	28	3	19	73
pyrethrum	0	0	0	0	32	26	9	18	0	0	0
hydrogen peroxide	0	0	0	710 000	290 000	340 000	160 000	20 000	0	0	0
deltamethrin	0	0	0	0	0	0	0	0	19	11	23
Antifungal											
malachite green	39	114	69	56	63	47	35	36	23	23	27
bronopol	0	0	0	0	0	0	0	0	0	128	448

Source: Norwegian Medicines Directorate/Statistics Norway 2002

Bath treatments can be costly to implement and may involve a degree of stress to the fish. Future trends may therefore be expected to concentrate on alternative treatment methods, or more specific drugs with little environmental activity, or perhaps treatments that can be neutralised prior to discharge. The development of acceptable administration methods for present compounds that avoid chemical discharge might be a useful intermediate alternative, but that presents considerable engineering challenges.

3. Factors Affecting Technology Application

STIRLING AQUACULTURE

3. Factors Affecting Technology Application

Having considered aquaculture from a management perspective, we now examine its wider context and interactions with broader social, economic, technological and political processes. The previous section considered aquaculture technology as solutions to multiple constraints, and focused mainly on practical production issues. This section examines the equally important social, economic and political influences, and the way in which these act as technology drivers. Firstly we focus on the marketplace, as this is the interaction that determines whether a company or technology is ultimately viable, and which also provides the greatest incentives for innovation; Secondly the regulatory environment, and in particular the agenda for sustainable natural resource management; Thirdly the wider context of technology development, from which aquaculture is able to benefit; and finally the commercial and economic context in which aquaculture business is conducted.

3.1 Market drivers

Aquaculture provides an increasingly important contribution to the market for aquatic foods. Traditionally the aquatic component of the wider market for foods has been dominated by products from capture fisheries. Though this currently remains, declining yields resultant from excess levels of fishing effort combined with the failure of fisheries resource management have reduced the supply from traditional sources at a time when demand for aquatic food products has grown. Increased demand may be explained by a range of factors including healthy eating, more diverse tastes promoted through wider food experiences, food safety concerns with alternatives and the delivery of products more convenient to consumers' lifestyle demands.

Aquaculture's response to changes in captured supplies has yet to become fully apparent. Early indications from the experience of farmed salmon, seabass and seabream have, reflected a rapid expansion based upon a technical and production-led response to (initially) high market prices. As supplies have grown, typically at rates of around 20% pa, there has been a significant reduction in market prices, which has fed producers' emphasis on cost reductions to maintain profit levels. Measures such as scale economies, technical innovation and structural change have combined to radically alter the characteristics of supply such that entirely new perspectives on the market are required. For example, whilst salmon farmers may have set out to produce fish intended to share traditional high-priced premium positions, this soon evolved into a much more diverse supply of products based upon the raw material of salmon species.

Other species can be expected to contribute further to this process. Internationally catfish, shrimp and tilapia, in addition to those mentioned earlier, have demonstrated global and cross-cultural market appeal. Just as has happened with other foods, internationalisation of the aquatic food products market has already become established and is set to grow rapidly. More recent developments on species still quite abundant from capture sources, such as cod, halibut, turbot, wolf-fish and other demersal species, suggest significant contributions have yet to be realised. The launch of such aquaculture supplies on the market presents interesting questions about relative market contributions and the respective positions that they might occupy. The market interaction, or substitution, between farmed and other captured supplies as yet is unclear. From a perspective of consumer food-choice it seems entirely plausible that substitution of captured by farmed supplies has occurred, and that much more will happen in future. Nonetheless econometric studies have identified little, if any, interaction. But this may be more to do with the limitations of the economist's toolkit based on the data available. Currently, aquaculture takes a significant share in global markets for shrimp, salmon, sea bass and bream, tilapia, catfish, carp, mussels, clams and seaweeds. In relatively undifferentiated products such as shrimp, in which capture and culture supplies may be less easy to distinguish, new markets are being served by products based on an admixture of farmed and captured supplies.

Species differences have been a primary distinguishing element in salmon, with Atlantic salmon focussed aquaculture product occupying a generally higher market position than the main capture sources of Pacific salmon. Other aquaculture products are also increasingly occupying the main markets for which continuity of supply and consistency of product are becoming increasingly demanded. For the wider range of aquaculture product, the still comparatively modest farmed contribution to global fish supplies is distributed across an increasingly diverse range of products in highly fragmented markets. As aquaculture production increases and a wider range of products is launched it seems that, despite possible labelling legislation, greater mixing with captured products will occur in the marketplace. More complex interactions are inevitable as the range of species expands, each with an attendant progeny of product launches, some specific others generic, to the aquatic foods market.

Historically fish has been to the forefront in advances in food science and technology, a position which has ensured comparatively high rates of new product development, comprising both evolutionary and radical innovations. Aquaculture has become, for some output at least, a further source of experimental raw material for the manufacture of an expanded range of aquatic food products. Indeed as the processing sector has had to contend with shrinking raw material supplies from indigenous capture sources, aquaculture product has provided a valuable fillip. Product diversification based upon traditional whole fish, fillets, steaks, portions, mince and analogue products, coupled with other non-fish ingredients has produced an extensive array consistent with the competitive demands of the market. The range of aquatic products has extended to incorporate much more technically sophisticated and complex components; yet at the same time examples of elementary simple product concepts such as headed and gutted fish, fillets and suchlike remain.

This trend has been encouraged and nurtured by the supermarkets, who have become by far the dominant players in Western retail markets, and increasingly in other regions. Given their prominence and power within the market for food, and their pivotal role in contemporary buyer behaviour, it seems axiomatic that they will play an increasingly important role in guiding and co-operating in the development of new species and their associated products. Other players within the food service sector also have their role, but generally their more fragmented structure, lesser market power and buyer characteristics tend to engender less involvement. Acceptance by the supermarkets can be expected to become a more integral part of the screening process for candidate species, their production systems and husbandry and the associated supply chains. Supermarkets, in conjunction with supplying processors, already play an important part in establishing key product specifications such as grade size, freshness, flesh colour and texture etc. and it is unlikely that this control will be relinquished.

Indeed as the range of candidate species expands and incorporates those bred for more specific product lines it seems logical to expect more exacting characteristics to be sought. For example where the flesh is intended for say a mince-based enrobed product lesser concern might be placed upon the external appearance of the fish as opposed to one where the skin-on fillet will be marketed. The extent of manipulation in the ongrowing process raises a number of currently contentious issues, not least being the use of GMOs[8] . Whichever way they develop, consumer concerns will undoubtedly play a major role in the signals sent through the production process.

Market signals are likely to become more central to the provenance and procurement of product, not least because of the range of recent food scares As the leading providers of food in most nations, supermarkets are heavily dependent upon the continued trust of their consumers and see themselves as guardians of that faith and credibility. Mindful of the adverse publicity that has surrounded some aquaculture activity, notably salmon, supermarkets will need to ensure that negative concerns are more proactively addressed and that by simple brand association they do not adversely affect the many other food items sold. In order to promote a more favourable image and to help counter possible negative perceptions the green attributes of the farmed product will figure more prominently than hitherto. Animal welfare concerns, traditionally voiced over poultry and other livestock sectors, have tended to leave the fish supply chains alone. However, as both wild and farmed stocks are associated with various environmental degradation, welfare and food safety issues, it seems likely that they too

8 Genetically modified organisms

will come under increasing scrutiny and require more proactive responses and counter-communications than have so far been employed.

Communications through product labels and more conventional promotional channels have sought to provide reassurance to consumers about a broad range of product attributes. Traditional information such as that detailing ingredients and nutrition has been supplemented by logos and other signifiers of production methods and standards including organic, farmed or captured, MSC[9] status. Debate exists as to what communications these increasingly complex configurations achieve; to many it seems simply confusing. Nonetheless the consumers' right to, and expectation of, more information suggests that whilst the message content may not diminish, the communications mechanisms employed may well need to alter. Existing technologies such as biosensors and encoded chips may provide some assistance in providing understandable information to consumers and further direction to the emergent aquatic food market. Whatever form these developments, what is clear is the need for greater understanding, and nurturing, of the relationship between consumers, producers and the markets' signals.

3.2 Policy drivers

Government policy and related regulation undoubtedly play a major role in shaping the industry. In Europe, numerous development initiatives have provided financial incentives and R&D support to stimulate aquaculture production in support of nutritional, economic and social goals. On the other hand, regulations place considerable constraints and financial burdens[10]. These arise from the responsibilities of government to ensure food safety, good employment practices, animal welfare, environmental protection, and increasingly, sustainable management of natural resources in the context of potential or actual conflicts between stakeholders. The latter is likely to be the most significant issue for the future development of the aquaculture sector, especially as they relate to the requirement for environmental goods (water, land, fuel and natural biological production) and services (ecological processing of aquaculture wastes).

For countries within the European Union, especially for international resource issues such as fisheries stocks and their exploitation, primary policy development takes place at the European level. Throughout 2002, the European Commission has consulted on reforms to the Common Fisheries Policy (CFP), including a strategy for sustainable development of European aquaculture[11]. The adopted policy on aquaculture will drive R&D and structural fund priorities over the coming decade, contribute to any legislative measures adopted at the EU level and influence national policy objectives. Initiatives such as the EU Water Framework Directive and the FAO Code of Conduct for Responsible Fisheries will also need to be taken into account. The present draft aquaculture strategy proposes three core objectives:

- Creating long term secure employment, in particular in fisheries dependent areas
- Assuring the availability to consumers of products that are healthy, safe and of good quality, as well as promoting high animal health and welfare standards
- Ensuring an environmentally sound industry

In specific terms, the strategy envisages accelerating sector growth rate from 3.4% to 4% per annum and growing employment from a base of 57,000 full time equivalent jobs by between 8,000 and 10,000 over the period 2003 to 2008. Envisaged actions include refocused priorities for public aid through FIFG[12] and R&D to concentrate on new species development, organic and environmentally friendly aquaculture, and on overcoming the constraints in aquaculture feed supplies.

The Scottish Executive is similarly developing a comprehensive strategy with similar objectives for aquaculture in Scotland[13].

9 Marine Stewardship Council
10 Scottish Quality Salmon cite over 50 items of legislation affecting aquaculture in the UK, and the situation in many other countries is similar.
11 EC COM(2002) 511, Brussels, 19.9.2002.
12 FIFG = Financial Instrument for Fisheries Guidance
13 A Strategic Framework for Scottish Aquaculture (DRAFT), Scottish Executive, 2002

3.2.1 Water management

Water resources are under increasing pressure, with Chapter 18 of Agenda 21, adopted at the UN Conference on Environment and development (UNCED, 1992) providing an international policy blueprint for future planning, and the EC Water Framework Directive the main regulatory tool for European implementation. Freshwater resources are most affected, but coastal waters are also recognised as requiring management. With water a primary requirement for aquaculture, developing policies on water resource management are likely to have considerable impact on the technologies employed.

Table 3.1: Maximum water requirements of industry and aquaculture

Product	Water use ($m^3\ t^{-1}$)	Water value (\$ m^{-3})
Alcohol	170	16
Cotton	450	11
Beef	42	48
Petrol	810	23
Shrimp ponds	55000	1.1
Salmonids	252000	0.018

Source: Muir & Beveridge (1987) and Phillips et al (1991)

Water use in aquaculture is determined by the species under culture, its life cycle stage, the scale and intensity of the aquaculture operation and the source water quality (especially temperature and dissolved oxygen). Extensive aquaculture relies on large volumes of water to support the stock but low flow rates, whilst intensive systems require lower volumes to contain the stock but with high flow rates. Measured in comparison with fish or shrimp production, water throughput figures of between 25,000 and 250,000 m^3/t are commonly reported[14]. However, in many systems, and especially water-based marine systems, there is no apparent consumption of this water (such as may occur in freshwater ponds in tropical countries where seepage and evaporation can cause losses of up to 20% per day). It is the alteration in water quality that is the key factor. The greater the relative throughput of water, the more dilute is the "effluent" from the aquaculture facility. For instance, aquaculture effluents typically have a BOD[15] of 2-12 mg/l, which compares well with treated sewage effluent (20-60), dairy effluent (1000-2000) or silage effluent (30,000 – 80,000). However, if based on BOD per unit of output, aquaculture compares less favourably, for instance producing 200 – 1300 kg BOD/t compared with 2-4 kg BOD/t for a dairy (Dolapsakis, 1996). Ultimately the significance of this output is related to the degree to which it is dispersed in the wider environment and the ability of the receiving environment to process the effluent. This is generally recognised in the regulation of discharge consents, which currently serve to limit aquaculture production at many marine sites. Any system of charging for waste output irrespective of environmental capacity could have a major impact on the financial viability of the aquaculture industry as it is presently structured. Most aquaculture systems rely on using uncharged water in order to be financially viable. The technology for minimising water requirements and effluent outputs is discussed in Section 4.3; The main problem being energy requirements, which presently have high actual and environmental cost implications themselves.

3.2.2 Land management

Competition for land, or more generally space, is well understood, and relatively sophisticated planning policies are commonly in place, especially for urban areas. By contrast, planning is often less well developed for the coastal zone, although this is gradually changing for instance with the draft EC Directive on Integrated Coastal Zone Management (COM/2000/547). Aquaculture is sometimes in apparent competition with other activities for space in the coastal zone, especially fisheries, tourism and

14 For comparison, cotton production uses 10,000 – 17,000 m3/t; a distillery 125-167 m3/t; and livestock 8-80 m3/t.

15 Biochemical Oxygen Demand: Standard indicator of water pollution due to organic materials

boating. In such cases it is rarely the actual area occupied by buildings and structures that is at issue, but rather the incompatibility between activities using the same wider area, and/or wider ecological resource. In contrast to water resources however, the land used for aquaculture almost always has a direct cost, through purchase and/or rent. In the UK this includes water-based aquaculture, as the coastal seabed is owned by the state and managed by the Crown Estate. Whilst costs are often related to the area occupied, they may take other factors into account such the turnover of the business. The pricing of land clearly affects the form and ultimately the viability of aquaculture. For instance large coastal pond systems are only viable where such land has a traditionally low value. In general, the land requirements for aquaculture are comparable with other agro-industry sectors. Fish farming requires between 0.003 and 1.7 ha per tonne of production whilst shrimp require 0.03 – 2 ha/t. These figures compare with 0.0008 ha/t for broilers, 0.1 – 0.2 ha/t for cereals and 1.3 – 10 ha/t for cattle (Dolapsakis, 1996).

At present, many conflicts are being resolved through application of a rigid planning process along with formal and informal agreements from resource users. The planning process for many western countries involved in intensive mariculture is based on the use of Environmental Impact Assessments. Here, issues relevant to multiple use of a system are incorporated into a formal document, which is submitted as part of the planning and siting application. Once in place, marine aquaculture sites are often subject to "area management agreements" which coordinated management of a distinct coastal area and set out practices that are agreed upon and adhered to by all users.

3.2.3 Energy conservation and ecological efficiency

Sustainability is now an almost routine inclusion in policy objectives, especially with respect to energy and natural resource use. However, measuring sustainability in this area is often difficult, given the complexity of global ecological interactions. In this section we examine some of the measures that have been employed to evaluate aquaculture sustainability.

Natural productivity

As discussed in Section 2.3.1, aquaculture is taking an increasing share of world fishmeal and fish oil production, whilst on a much smaller scale, natural brine shrimp are also exploited for hatchery feeds. Some branches of aquaculture are still reliant on natural sources of seed stock or broodstock. The overall management of natural biological productivity, ownership of the resources and their sustainable and equitable exploitation is likely to remain a challenge for policy makers for the foreseeable future. One of the perspectives sometimes applied to this type of natural resource management is that of thermodynamics. As with all food production, the energy value of farmed fish is lower than the energy input during production. For farmed salmon, approximately 18.5 units of energy are required to produce each unit of energy contained in the final edible product, whilst for mussels, this is reduced to a ratio of 3.2 to 1. Overall, the gross energy usage of aquaculture is comparable to terrestrial livestock (Between 116 and 3780 MJ/kg of protein produced). Semi-intensive pond-based aquaculture and shellfish culture that does not require any artificial feeds, use even less gross energy than grazed cattle. However, intensively fed aquaculture systems utilise more energy than poultry, mainly due to the higher trophic level of marine fish (carnivores rather than herbivores or omnivores). For cage-based mariculture, the usage of fishmeal is a particular constraint and energetic cost, representing up to 80% of input energy. The production of 1 tonne of carnivorous fish requires the capture and processing of approximately 3.5 tonnes of industrial fish, rendered to 0.7 tonnes of fishmeal. In comparison, typical natural food chain efficiencies that are usually closer to 10:1.

Table 3.2: Comparative energy usage for different aquaculture and livestock systems

Product	Production system	Energy usage (MJ/kg protein)
Mussels	Intensive, long-lines	116
Salmon	Intensive, cages	688
Grouper/seabass	Intensive, cages	1311
Tilapia	Semi-intensive, ponds	0-199
Catfish	Intensive ponds	582
Catfish	Intensive raceway	3780
Carp	Intensive, recirculated	3090
Beef	Rangeland	170
Beef	Feedlot closed	513
Beef	Feedlot open	1350-3360
Pork	Intensive	595-718
Poultry	Broilers	370

Source: Stewart, J.A. 1995

Table 3.3: Contribution of energy expenditure in selected aquaculture systems

	Salmon, intensive cage farm	Grouper/bass intensive cage farm	Tilapia, semi-intensive ponds	Mussels, longline
MJ/kg edible product	142	262	40	11.6
MJ/kg protein	688	1311	199	116
	Contribution to energy expenditure (Percent)			
Structures	6	2	3	48
Equipment	<1			5
Vehicles	<1			5
Feed	79	78	97	
Stock	3	10		
Fuel & power	4	7		42
Others	6	3		

Source: Stewart, J.A. 1995

Table 3.4: Energy content of aquaculture products in comparison with other meats

Product	Energy content kJ/kg	Energy content GJ/tonne
Farmed Atlantic salmon (edible flesh, raw)	7,660	7.66
Wild chinook salmon (edible flesh, raw)	7,530	7.53
Wild Atlantic cod (edible flesh, raw)	3,430	3.43
Grouper (edible flesh, raw)	3,850	3.85
Blue mussel (edible flesh, raw)	3,600	3.6
Chicken (meat only, raw)	5,730	5.73
Beef (meat and fat, raw)	11,840	11.84
Pork (loin meat & fat, raw)	8,280	8.28

Source: (USDA National Nutrient Database for Standard Reference www.nal.usda.gov)

Non-renewable energy

Energy policy tends to be managed at a higher level than individual agroindustry sectors. However, the relative cost of energy will play a major role in shaping the aquaculture technologies of the future. Fosil fuel prices are expected to rise with growing scarcity and policies to reduce carbon emissions. However, over the long term, alternative and less polluting energy sources are likely to be developed, perhaps ultimately leading to a reduction in cost. Atlantic salmon production in cages requires approximately 50Kcal of fossil energy input per Kcal of protein output, compared with 29 Kcal for Atlantic salmon fisheries and 20 Kcal for cod fisheries. However, the figure is substantially lower than for many lobster and shrimp fisheries. Intensive land-based mariculture would have a much higher requirement. Systems that pump water, use tanks, and perhaps water treatment systems are the least energy efficient, surpassing intensively fed beef stock.

Table 3.5: Fossil energy usage in aquaculture and fisheries

Seafood type	*Kcal fossil energy input/Kcal protein output*
Sea ranching of Atlantic salmon (Delayed release)	7
Mussel rearing	10
Sea ranching of Atlantic salmon (Conventional)	12
Cod fisheries	20
Cage-farming of rainbow trout	24
Atlantic salmon fisheries	29
King salmon fisheries	40
Cage farming Atlantic salmon	50
Lobster fisheries	192
Shrimp fisheries	3-198

Source (Folke and Kautskey, 1992)

Table 3.6: Comparison of agricultural systems with respect to proportion of energy derived from fossil fuels

Type of system	*Notes/main products*	*% total energy input derived from fossil fuels*
Pre industrial agriculture: New Guinea	Shifting mixed crop/livestock	0
Pre industrial agriculture: Wiltshire, UK	Mixed crops and sheep	2
Semi-industrial agriculture: Java	Taro, Coconut, fish and seafood	54
Semi-industrial: India (1955)	Sugar cane, rice and millet	58
India (1975)	Sugar cane, rice and millet	77
Fully industrial agriculture: Moscow	Potatoes, oats, wheat, barley and hay. Some livestock	96
Fully industrial agriculture: S. England	Wheat, barley, oats, fodder crops, cattle, sheep and pigs	99
Seaweed culture		2-95
Mussel culture		2-15-29
Cage salmonid culture		2-13-19

Sources: Bayliss-Smith, T.P (1982) and Muir and Young (1998).

Ecological analysis

As commercial economics are often considered to undervalue the environmental contribution, various approaches have been taken to quantifying, and if possible valuing, the natural resources used by activities such as aquaculture. These include ecological footprinting, adjusted net savings and triple bottom-line accounting. Whilst problematic, these techniques provide useful perspectives for policy development, and may have some influence on the other direct modifiers of aquaculture system design.

3.2.4 Employment and social policy

Both central and local government usually develop policies that emphasis the importance of employment and economic development. The aquaculture industry has often proved an attractive way to meet these objectives, especially in economically fragile rural coastal areas that are suffering from contracting capture fisheries industries. For instance, if upstream and induced income expenditure multiplier effects are also considered, salmon farming in Scotland is probably supporting in the region of 1 job per 20 tonnes of production (up to 7000 jobs at present), and each job is generating around £43,000 per year for the Scottish economy. As in other sectors though, employment opportunities are moderated by the drive to improve productivity. In Scotland, this rose from around 15 tonnes per person per annum during the late 1980s to 110 tonnes by 2001 (Fisheries Research Service, 2002). Norwegian figures are higher (132 tonnes/person in 2000) and only just below productivity for the fisheries sector (135 tonnes/person in 2001). The actual number of people employed in marine fish culture has fallen in Norway by 50% since 1988, whilst in Scotland it has declined by over 6% since 1990 (the year with the highest labour numbers). Downstream employment in processing and distribution is more significant in employment terms (1.7 times in 1996 (PACEC & Stirling Aquaculture, 1998)). Future patterns of employment depend on the technologies employed and degree of expansion in the industry. Further improvements in productivity appear likely, although job numbers could be increased through diversification both in production and processed products.

It is not only the number but also the quality and mix of the jobs and the contribution they make to social cohesion and welfare that must be considered. The 1998 PACEC/Stirling Aquaculture study of the economic impact of salmon farming in Scotland found 85% of employees in the farming sector to be male and predominantly manual workers (13% skilled, 49% semi-skilled and 19% unskilled). The remaining 18% of the male employees were non-manual, mainly managers, sales staff and professionals. Around 61% of the female staff were manual workers (38% skilled or semi-skilled) and 22% clerical, although 13% were managers or professionals. The processing sector has a higher male to female ratio, with around 59% of employees male, and also a higher ratio of manual workers (91% of males and 84% of females), predominantly semi-skilled manual and unskilled manual. Efficiency gains are likely to reduce the percentage of employees in unskilled positions, and most large companies have active staff development programmes.

3.3 Technology drivers

As a modestly sized industry, with limited scope for endogenous R&D aquaculture has borrowed heavily from other sectors for its technology inputs, and adapted these for more specialised objectives. For that reason, generic advances in biotechnology, communications and information technology, sensors, materials and marine engineering will all play a role in driving further advances in aquaculture technology. The sector is mostly driven by incremental and evolutionary advances, such as the design of more cost-effective and reliable cages, improved handling, feed delivery and water treatment systems. Advances in biotechnology, and especially genetic engineering, offer potential for greater step changes in performance, although their acceptability to consumers remains a key issue. It might also be argued that technical constraints are a greater driver of R&D than technology opportunities. The finite nature of global fish oil supplies and the potential impacts on aquaculture development within this decade, together with a continuing and possibly increasing need for biosecurity[16] are likely to drive much of the broader sectoral R&D over the medium term.

16 Isolation of the aquaculture stock from the environment in order to prevent the transfer of disease in either direction

In practice, it is not the existence of a technology solution that drives its uptake, but the cost-benefit ratio it delivers and the additional margins above existing investment (threshold effect).The expansion of the industry can therefore be a technology driver itself.As the market grows for equipment, feed and pharmaceutical supplies, it becomes financially viable for suppliers to invest in R&D, tools and production processes that lower unit costs so as to offer technically superior products to the aquaculture market at financially advantageous prices for the producer.A further area of technology, that within food processing and distribution, also offers potential gains to the sector in widening the scope for diversification, expanding markets, and increasing the broader levels of demand for aquaculture product.This is not assessed more specifically within this review, but its influence in the scope for growth, profitability and hence potential for investment in new production technology, must be recognised.

3.3.1 Materials technology

Further advances in materials technology are anticipated, especially from the expanding discipline of nanotechnology.This might include stronger or non-fouling materials for containment equipment; materials that can be converted, recycled or biodegraded at the end of useful life; and new types of filter materials for water treatment. Polymer-based electronics are expected to allow computing "intelligence" to be built into materials, certainly including clothing, but perhaps also nets, ropes, tanks and pipes.

3.3.2 ICT

Use of information and communications technologies (ICT) is increasingly important in aquaculture. Computerised monitoring and control systems are regularly employed in the more advanced hatchery systems using water treatment and environmental control systems. Computerised feeding systems are also quite common, even on large cage systems, with increasingly sophisticated methods for monitoring feeding activity and algorithms for controlling feed dispensation.The most advanced use information from current meters, sonar or video to minimise feed wastage (and hence environmental impact).With more sophisticated computer analysis, video and sonar images can analyse behaviour patterns to provide indications of ill health, predator attacks, breaches in the cage net, algal blooms or other water quality problems.When linked to appropriate control systems, serious losses might be avoided. Such systems also employ devices for fish counting and length/weight assessment, to improve feed control and to help with harvest scheduling.

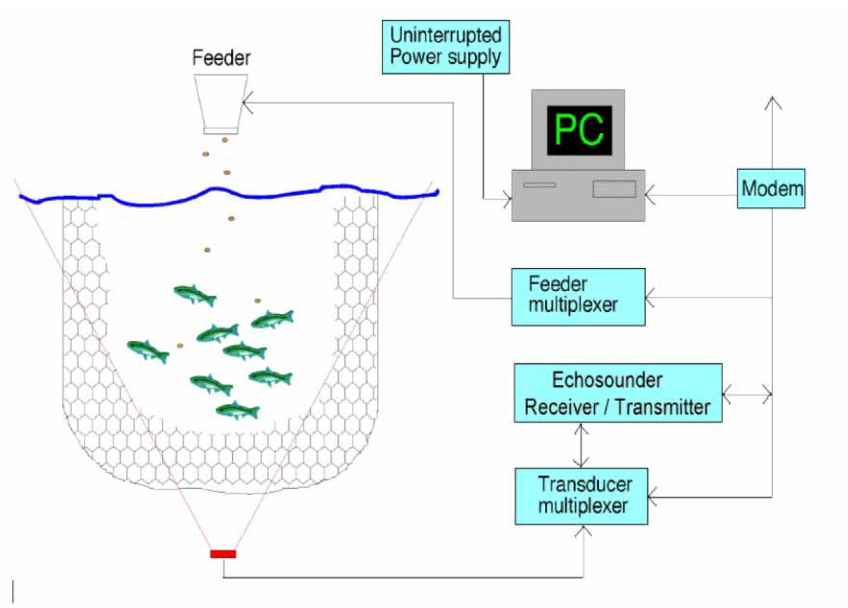

Figure 3.1 Outline of the "Cage-eye" system design, integrated with computer control adapted from Bjordall et al, 1993).

A problem for smaller companies is that such systems are often proprietary and do not integrate easily to provide added value. Large companies with in-house ICT staff now use relatively sophisticated information systems and are progressively implementing full traceability with linkages between farm and processing factory databases. Smaller companies are more variable in their uptake of ICT. A survey of Scottish salmon farms in 2000 (Superior Systems, unpublished) found 67% of aquaculture companies used computerised stock records (89% of larger companies) and 61% had computerised accounts (100% of larger companies). Around 50% of the companies had access to the Internet and used e-mail at that time and 22% had their own web pages. These proportions are likely to have risen, with the feed companies making more use of web pages and e-mail for customer support. Greater use of ICT is specifically promoted in the Draft Strategic Framework for Scottish Aquaculture[17].

R & D in the ICT sector is exploring technologies such as wireless self-organising networks, intelligent materials, new generation low-cost sensors, low-powered computing and next generation storage, display and interface approaches. These technologies will undoubtedly be incorporated into aquaculture systems as cost-benefit allows and when reliability is established. Possible technologies might include cage nets that have the intelligence to adjust to different current speeds and directions, or to alter shape to minimise losses and alert farm staff when a tear occurs. Some fish might be equipped with advanced physiological sensors that continually relay information on health, stress, behaviour, energy expenditure, nutrient absorption or surrounding water quality to centralised computers, or to feed controllers and anti-predator devices etc., to allow health and other problems to be detected before they cause serious losses. Greater information on fish growth and physiology, and perhaps directly flesh quality (e.g. lipid content), might be better integrated with processing and marketing operations, such that a wider range of market requirements might be met more reliably from aquaculture. More widespread and comprehensive real-time monitoring of the marine environment may help to protect against the effect of harmful algal blooms and jellyfish swarms, for which defence mechanisms are now being researched, and will help further our understanding of the wider environmental interactions of aquaculture so that mitigation measures can be improved.

3.3.3 System technologies

Whilst the basic elements of aquaculture systems are unlikely to change, their expression with respect to physical facilities, scale and location are open to further innovation. In particular, there could be opportunities for economic synergies by linking offshore wind and wave power stations, or other marine infrastructure (ocean thermal energy conversion, CO_2 sequestration and mitigation, oil/gas installations etc) with offshore fish and shellfish farming. Over-capacity in the capture sector might also provide opportunities for combining elements of fisheries and aquaculture

3.4 Commercial drivers

Marine fish culture in Northern Europe has been largely dominated by the activities of Norwegian investors, who have driven expansion and consolidation, at times ahead of market capacity. Norwegian companies are especially active in Scotland, Ireland Canada, Australia and Chile, but are much less significant in Southern Europe, where there has been less consolidation in general. Some of the major Norwegian aquaculture companies are now in financial difficulties, suggesting that the rate of investment seen in the mid and late 1990s may not continue. Further progress with cod farming may drive a second round of investment, but this will mainly be in hatcheries, as existing salmon facilities can be used or adapted for cod growout, and while some expansion in capacity may occur, it could also to varying degrees substitute for salmon stocks yielding poorer financial returns.

Continuing consolidation is not inevitable, as some major companies may focus more on the value-adding parts of the business and reduce exposure in the relatively risky and low-margin area of production. There may also be greater specialisation, for instance in hatcheries and breeding programmes. Technical breakthroughs that allow production of new species at viable prices will remain attractive to investors, assuming demand generally remains ahead of supply, though they are now generally more aware of the scale of opportunity for profit.

17 Scottish Executive, 2002

4. Aquaculture Systems Evolution

STIRLING AQUACULTURE

4. Aquaculture Systems Evolution

Having considered specific technology issues and key sector influences, we now take a broader look at the current or potential types of marine aquaculture systems, and the ways in which they might develop in the future. The main system approaches considered are: Near-shore, offshore, on-shore intensive, on-shore integrated and free-range.

4.1 Near-shore aquaculture systems

Traditionally, near shore aquaculture has been carried out in sheltered areas and places with ease of access to boats and culture equipment. The simple original technology used for aquaculture, mainly cages or rafts, was unable to withstand the rigors of waves and wind further from the coasts. These established sites have been the mainstay of marine aquaculture, and are still used to utilize the established sea- and shore–based infrastructure.

The expansion of the near shore aquaculture in these sheltered areas has lead to an environmental management and regulation system based on the concept of discovering the potential for aquaculture without exceeding the carrying capacity for an identified coastal area. This is an attempt to calculate how much production can be sustained without unacceptable impacts on the environment. Examples include the approach[18] used in Norway for the environmental regulation of Atlantic salmon farming (Bergheim *et al*, 1991; Ervik *et al*, 1997) and calculation of food supply (particulate organic material) for coastal mussel farming (Carver & Mallet 1990). This approach to effective use of near-shore environments requires careful use of resource from initial modelling of environmental inputs and their fate, and monitoring. Mass balance and dispersion models are used in near-shore aquaculture to calculate environmental inputs of both soluble and solid wastes. Many of these are based on a single area or cage site approach, but are less effective for regulation of a wider area (Henderson *et al*, 2001) and of limited use in the implementation of coastal management plans. More appropriate in this respect is the use of a Geographic Information System (GIS) approach which can employ a holistic approach to coastal resource management (Perez *et al*, 2002), and be used for the estimation of the carrying capacities coastal areas and more appropriate siting of coastal aquaculture systems based on both environmental and management factors (Ross *et al*, 1993).

As marine fish culture leads to an output of nutrients, the development of associated aquaculture activities that rely on nutrient inputs can provide a better-balanced system that allows greater fish production at sustainable levels than might otherwise be the case. For instance, seaweed culture may directly utilize inorganic nutrients (nitrogen, phosphorus) whilst shellfish culture will rely indirectly on inorganic nutrients as they mainly feed on microalgae, which like seaweed rely on inorganic nutrients, but also on directly on fine particulate organic waste from fish farming. In practice, considerations such as tides, currents, environmental variability and production cycles make carrying capacity calculations exceedingly difficult, although progress is being made. At the practical level, there is some evidence that the use of seaweed and bivalve culture in close proximity to marine fish farming, can have the effect of a natural biofilter (e.g. Angel *et al* 2001).

18 LENKA-MOM

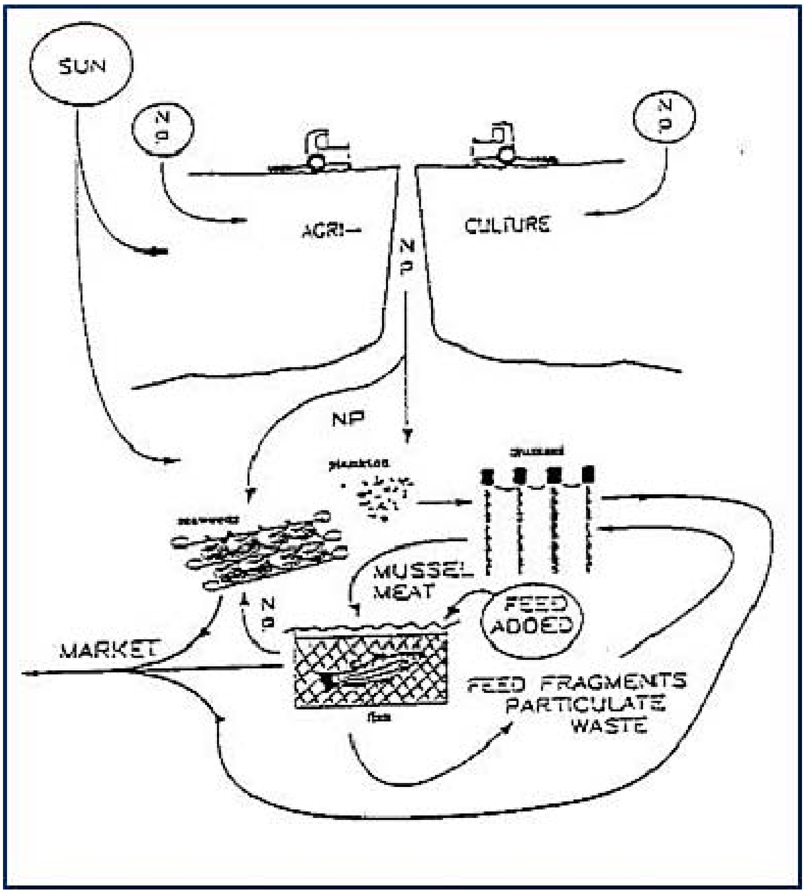

Figure 4.1: Conceptual diagram of integrated coastal mariculture from Kautsky & Folke (1991)

Many near-shore cage systems are often of simple design consisting of a framework of between 6 and 50 square steel cages in a block with a simple net suspended below. Larger cages are also used such as circular plastic cages which are either individually moored or moored in groups of 4 to 8 to maximise the number of fish within a production area. Raft and line shellfish culture has changed little in principle over the past two decades, but significantly in scale and in development of more specialised equipment. With increase in aquaculture activity within enclosed coastal bays, with limited water exchange with the ocean, more of the capacity of these bays to assimilate waste and provide food and oxygen is used up. Many attempts have been made using management and technological approaches to use the available carrying capacity to better effect. Much of this work is still ongoing but is tied up with maximising use of food and feeding efficiency, and is therefore beginning to be employed extensively within the fish farming industry. Examples of such systems include uplift apparatus where any uneaten food is collected at the bottom of the cages and pumped to the surface, indicating feeding should be ceased. Video cameras are also commonly employed to monitor feeding response and improve feeding efficiency. More sophisticated systems providing interactive feed-back are now in operation. These are feed management systems that deliver feed based on the known behaviour responses of the fish to feeding (e.g. throughout the day or night) and a sensor that minimizes waste input by shutting off supply when uneaten food is detected. Two systems are commonly used; Aquasmart and Storvik. The former has been shown to increase feeding efficiency significantly and the latter utilizes both sensors and an uplift system to re-use uneaten food. These system are capable of giving a 23% decrease in the amount of particulate material falling to the seabed (Kadri *et al*, 2001).

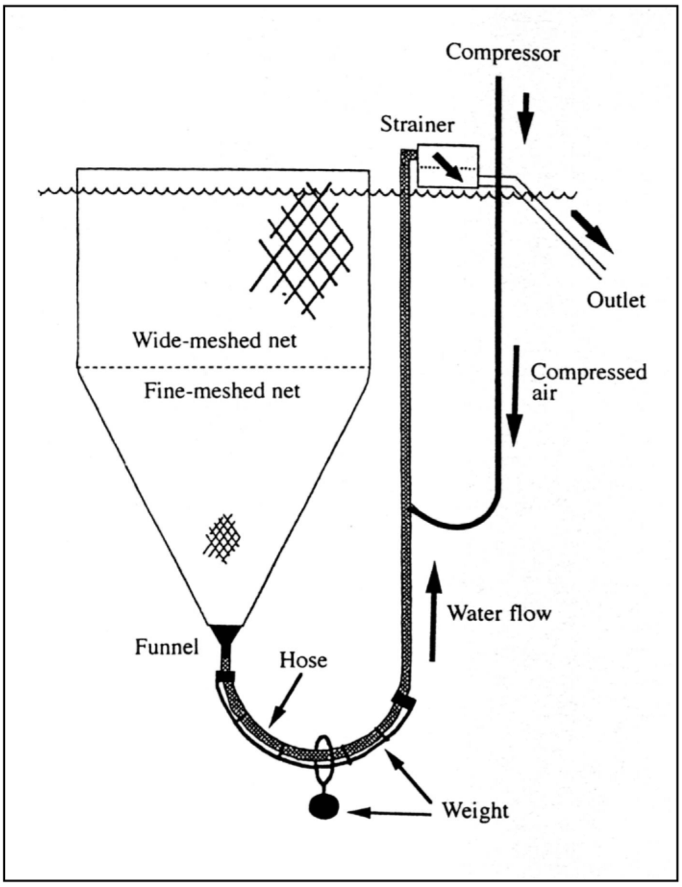

Figure 4.2: Schematic diagram of the "lift-up" system (from Ervik et al*, 1994)*

Another approach to using technology to mitigate and minimize waste inputs is through single point moorings (Goudey *et al*, 2001), promoted by Ocean Spar Technologies, USA. Here a production cage is moored on a single point allowing the cage to move in response to the environment. This allows the formation of a "watch circle" (Goudey *et al*, 2001) where the position of the cage depends on the sum of the environmental forces (e.g. tides, wind and waves), thus spreading the accumulation of organic material. Preliminary analysis indicated that there is a two to seventy fold reduction in the deposition of waste on the seabed, depending on the current and the mooring geometry, although risk of mooring failure may be increased.

Other "cage" systems prevent any interaction between aquaculture waste and the wider environment and is seen as the ultimate solution to environmental impacts. This technology does not use net cages but polypropylene bags that exclude the outer environment. Thus all waste from uneaten food and faecal material is collected (Future Sea Farms, Nanaimo, BC). Here a "cage-bag" system is used where water is pumped into bags from deeper waters and waste are collected prior to the water leaving the bag. Until 2001 these systems had only been used in Canada and Chile though they are being implemented further afield. There are also implications for management of escapes and disease transfer using these systems. However, they require highly sheltered environments and have considerable limitations as to their use, which is under consideration (Taylor *et al*, 1998).

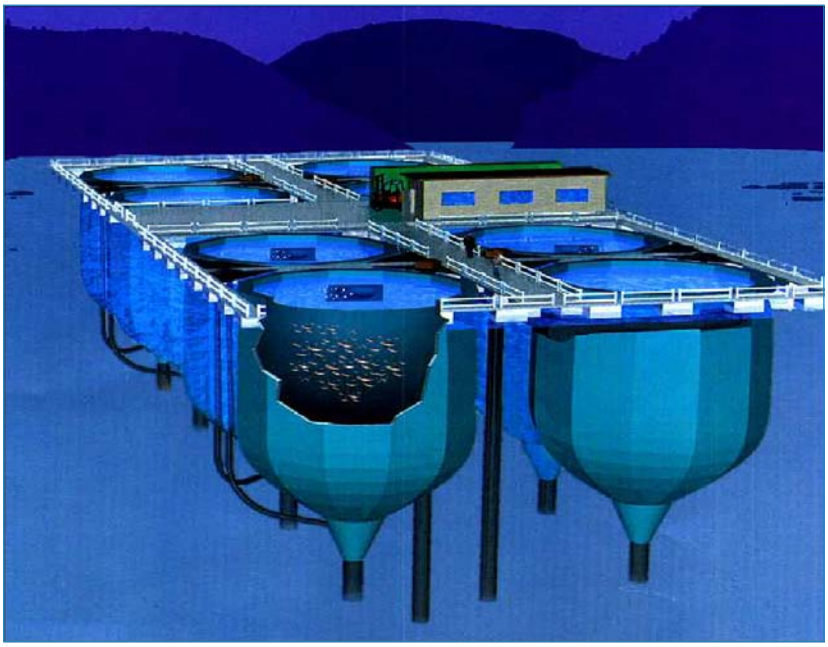

Figure 4.3: Illustration of a floating closed cage system operation (Future SEA Farms Inc.)

4.2 Offshore aquaculture systems

"Offshore" is defined in various ways, but is generally understood to mean marine sites that are unprotected by landmasses and are therefore fully exposed to prevailing wind and waves. Other definitions have included distance from shore (usually 2+ km), water depth (50+ m), and environmental conditions (e.g. wave heights exceeding 5 m). The adoption of offshore aquaculture is driven by limits on production from near-shore sites, developing the model of near-shore cage farming and adapting it to the harsher environmental conditions of offshore sites. Approaches adopted have included flexible floating cages (e.g. Bridgestone, Dunlop and Ocean Spar Net Pen), large rigid floating steel structures (e.g. Aquasystem 104, Pisbarca, Cruive, Marina System Iberica and more recently Storm Havbruk), rigid and flexible semi-submersible cage designs (e.g. Farmocean, Refa, Ocean Spar Sea Station) and rigid submersible systems (e.g. Sadco, Marine Industries, Sea Trek and Trident). There are a variety of technical challenges to the design of such systems. As environmental forces, especially from waves, is greatest at the surface, submersible or semi-submersible cages where most of the structure is below the highly dynamic surface zone, offers potential advantages. It is not only the cages and nets that have to be protected from wave damage, fish stocks are also susceptible if the water mass in which they are swimming is moving rapidly in relation to fixed structures. Flexible systems that are somewhat wave compliant have proved more robust and cost effective. The main problems with flexible and submerged systems are associated with servicing the cages for stock movements, feeding and harvesting.

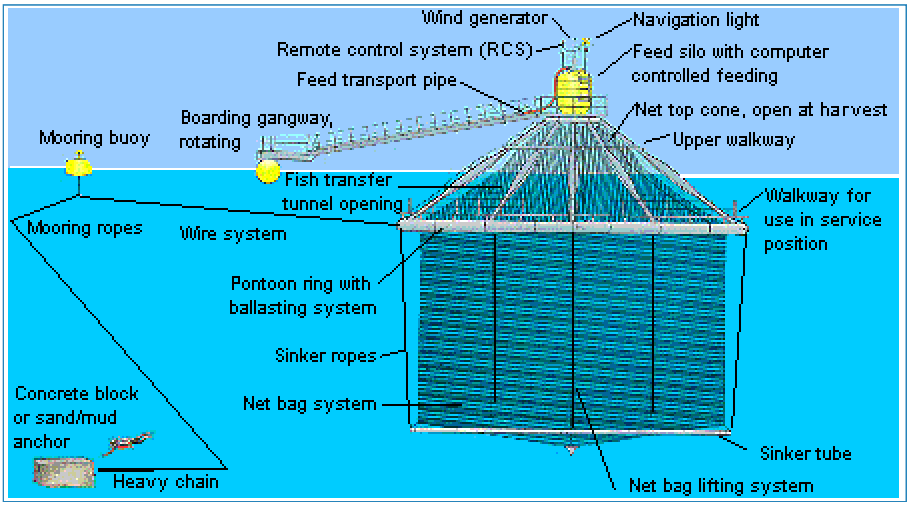

Figure 4.4: Diagram of the Farmocean semi-submersible cage system (http://www.farmocean.se/)

As offshore aquaculture systems require more robust and specialised equipment, including vessels, feed and net handling gear, they are inevitably much more expensive than near-shore counterparts. This drawback can potentially be offset by increased economies of scale in offshore systems. This has particularly been the case with Bridgestone cages, some of which can hold over 500 tonnes of fish. The Storm Havbruk cages currently undergoing trials in Norway have even greater capacities of up to 900 tonnes of fish. In contrast, Farmocean and other submersible and semi-submersible designs have capacities around 100-150 tonnes, a figure which is now matched by the largest plastic near-shore cages (e.g. Fusion Marine) that can be used in semi-exposed locations at much lower unit cost. Utilising larger holding capacities increases the scale of any losses if the system fails, and this, combined with the inherent difficulties in robust offshore engineering, discourages investment so long as safer alternatives exist. However, with many near-shore sites limited to 1000 tonne or lower capacities, continued expansion of marine aquaculture could be facilitated by a move offshore. The growth of the tuna farming industry in Australia, the Far East and the Mediterranean, is a potential driver for larger plastic and rubber cages. Models built around an oil platform-style service facility with satellite cages have been used in Japan and Spain. The Storm Havbruk system also includes accommodation and service facilities. Another approach is the self-propelled, ocean-going farm, designed to overcome the need for costly moorings in deep water, and the inevitable stresses between moorings and cage structures, a model design has been developed at The Centre for Fisheries Engineering Research, USA, based on the Ocean Spar Sea Station cage, and an old oil tanker is being used for abalone culture in Australia. Other approaches to offshore mollusc culture are being developed. Typical drum-type floats for long-lines have been replaced by pencil floats in trials in France, a submersible long-line has been designed in Canada, and Scottish company Subsea Shellfish, has developed (although not yet marketed) a plastic submersible shellfish platform with complementary service gear.

Figure 4.5: Platform cage design from Marina System Iberica http://www.msicom.net/

Offshore aquaculture has been a reality for at least 15 years, with continuing uptake and systems development, albeit little in the UK. The scale of investment required, the need for matching infrastructure and insurance cover, issues of demand and alternative production options, all suggests that development in this direction will be gradual, with much R&D still required. It may also be highly species dependent, suited especially to mass-market fish that are well adapted to open sea environments, such as tuna and salmon. However, new drivers might emerge (e.g. synergistic activities as envisaged in 3.3.3) that would afford continued growth of aquaculture with minimal localised environmental impact, enhanced fish welfare and perhaps improved utilisation of resources. However, wider ecological issues remain relevant, as does the issue of staff health and safety, with offshore being one of the most dangerous environments in which to work.

4.3 On-shore intensive and recirculated aquaculture systems

On-shore tank-based aquaculture systems are quite widely used, especially for hatcheries and rearing small fish. A flowing water supply is required to flush away metabolites and waste products, and to replenish oxygen supplies and maintain stable water quality conditions. The water supply may be arranged as a single-pass, discharged after passage through the fish tanks, or may be recycled through a treatment process and re-used many times. The use of recycled systems are often advocated as a means of overcoming many of the concerns about marine aquaculture, as the system can be highly isolated from the environment. Tank-based farms have not proved economic for salmon growout in the past, and there may be considerable planning issues if major expansion of this kind of unit were envisaged in prime coastal areas. Technically, it might be possible to locate farms in industrial areas, close to major markets (preferably also close to a seawater source, but with further technology development, not absolutely essential). With the present state of technology, the main brake is firstly the capital cost of such systems, compared with cage-based aquaculture, and secondly high energy costs that usually add substantially to overall operating costs. These can be sustainable for high unit value species or life stages (e.g. hatcheries), due to the improvements in performance that can be obtained using a better-controlled environment. However, the same advantage is not apparent in the grow-out of species such as salmon, sea bass and sea bream and most investments in this area have failed as uncompetitive. The acceptance by consumers of products reared in intensive recycle systems also remains to be robustly tested. The situation might be radically altered if genetically modified fish were accepted on the market. Such systems would be ideal for minimising the risk of escapees and other ecological interactions, whilst the improved performance of the stock under controlled conditions might compensate for the additional investment and operating costs.

Although recycle systems are relatively common, there is considerable diversity in their design, with components often custom-fabricated due to low sales volumes making mass production unviable. Reliability can also be an issue, in part through engineering weaknesses, but further research and development is also needed to fully understand and optimise system and component interactions. With recirculation already a key technology for countries with limited water resources, or where breeding programmes require a high degree of biosecurity, further progress in system design is anticipated. Future systems are likely to have better integrated components, optimised for energy use, commoditized and scaled up for production use. Treatment and disposal of wastes from the system remains an issue for further development, with the use of anaerobic digestion one approach currently under investigation.

Most recycle systems are based on maintaining clean water in the culture tanks and use bacterial processes in separate filters for water purification. An alternative approach, apparently suited to detritus feeding shrimp and tilapia, is activated suspension systems, where bacteria are encouraged to flourish within the culture tanks or ponds, breaking down wastes and recycling nutrients directly. The cost savings are significant and with control improvements, may provide a commercially viable solution for some sectors of the industry. However, these are more likely to impact warmer water systems, and hence export suppliers to European markets.

4.4 On-shore integrated aquaculture systems

The concept of integrated aquaculture dates back hundreds of years, widely practiced in China centred on freshwater ponds. The principle is based on optimising ecological efficiency by using the waste output or by-products from one farming activity as inputs to another. In China, elaborate systems have developed involving livestock, poultry, fishponds, horticulture and silk production. The principle is now being seriously evaluated for land-based marine systems, integrating several mariculture activities, but each maintained in separate compartments for better overall control. For instance, fishpond effluent is fed into specialized microalgae production ponds, which are used to feed bivalve shellfish. Additional nutrients are reclaimed through the production of the marine plant, *Salicornia spp.* by passing the discharge effluent through wetlands.

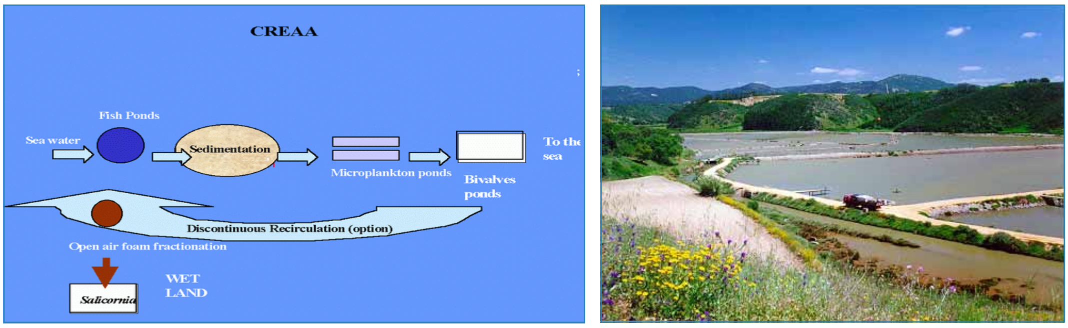

Figure 4.6: Example integrated mariculture system (see http://genesis.ocean.org.il/) and photograph of coastal ponds in Portugal where such systems might be applied.

The optimization of integrated systems is most difficult in temperate climates where there are clear seasons and different production cycles for the various aquatic products. Management options, such as the use of some therapeutants, might be constrained by the potential impact on other units of the system. In many regions, the limited availability of coastal land suitable for integrated systems may constrain adoption, although elsewhere it might be a means of rejuvenating traditional pond systems. As this method of farming is closer to organic aquaculture production, it might be expected that products from integrated systems could obtain some premium on the market, although this remains to be fully tested. The primary fish (or shrimp) product still requires feed inputs from external sources, although the rearing of omnivorous or herbivorous species can help reduce the demand for fishmeal and oil. Overall, integrated aquaculture offers a sustainable means of improving aquaculture production in many areas. It is not a complete answer to the many issues raised by aquaculture within the coastal zone, but could provide an acceptable approach for some species where more industrial approaches are not appropriate.

4.5 Free range aquaculture systems

A development of penned, or contained aquaculture, is he concept of free range aquaculture. This has developed from sea ranching of commercially important fish or shell fish species, where hatchery reared stocks are released into marine or brackish waters where they can propagate or grow on natural foods, until they reach harvestable size, when they are captured using traditional fishing techniques. Throughout the world 27 countries employ ranching as an alternative to aquaculture. Japan leads the world with a total of 80 ranched species including Pacific salmon, cod, blue crab and grouper. Currently salmonids are the most widely stocked group of fish. To give an example approximately 400,000 tonnes of salmon are ranched in Japan, Russia and North America annually.

Ranching has advantages and disadvantages over traditional pen aquaculture, primarily in terms of initial cost benefits. Feeding, the greatest part of growing costs, is only paid through the juvenile production periods when they are grown in tanks. Similarly these tank facilities are only required through this early stages and therefore need only be of limited capacity. The benefits are also shown by the EER[19], which are 13% and 25% for tank

19 EER – Energy efficiency ratio = energy produced / energy cost of production

production and ranching of salmon, respectively. However, the great disadvantage is the limited survival or return of fish at between 1 and 15%, to realise original investment, compared for instance with cage culture, in which about 90% of fish grown are harvested.

Several techniques have been used to increase the number of fish that come to harvest through ranching. These include partial enclosure of the system, using barriers to fish migration or artificial reefs for provision of habitat. These have been effective to various degrees but the logical extension to this is known as the concept of "Free Fish Farming at Sea" (FFFS) (Stirling Aquaculture, 1998). Here hatchery reared fish are conditioned in either tanks or cages to specific acoustic signals and subsequently released into the open sea. A number of additional facilities can be installed, such as artificial reefs to provide stimulus and conditions for the fish to stay in the general locality, and which may provide additional habitat for feed supply and protection from predators. A range of methods may be used to separate the fish from open sea areas, such as acoustic curtains, natural reefs or physical barriers. The acoustic conditioning is used to signal to the fish a feeding station where artificial diets are used and eventually to attract the fish to a position where they can be harvested using traditional fishing methods. This method of aquatic production may apply to a range of species, environments and management regimes. There is also the potential to develop a number of specific techniques or variations to suit local coastal environmental conditions.

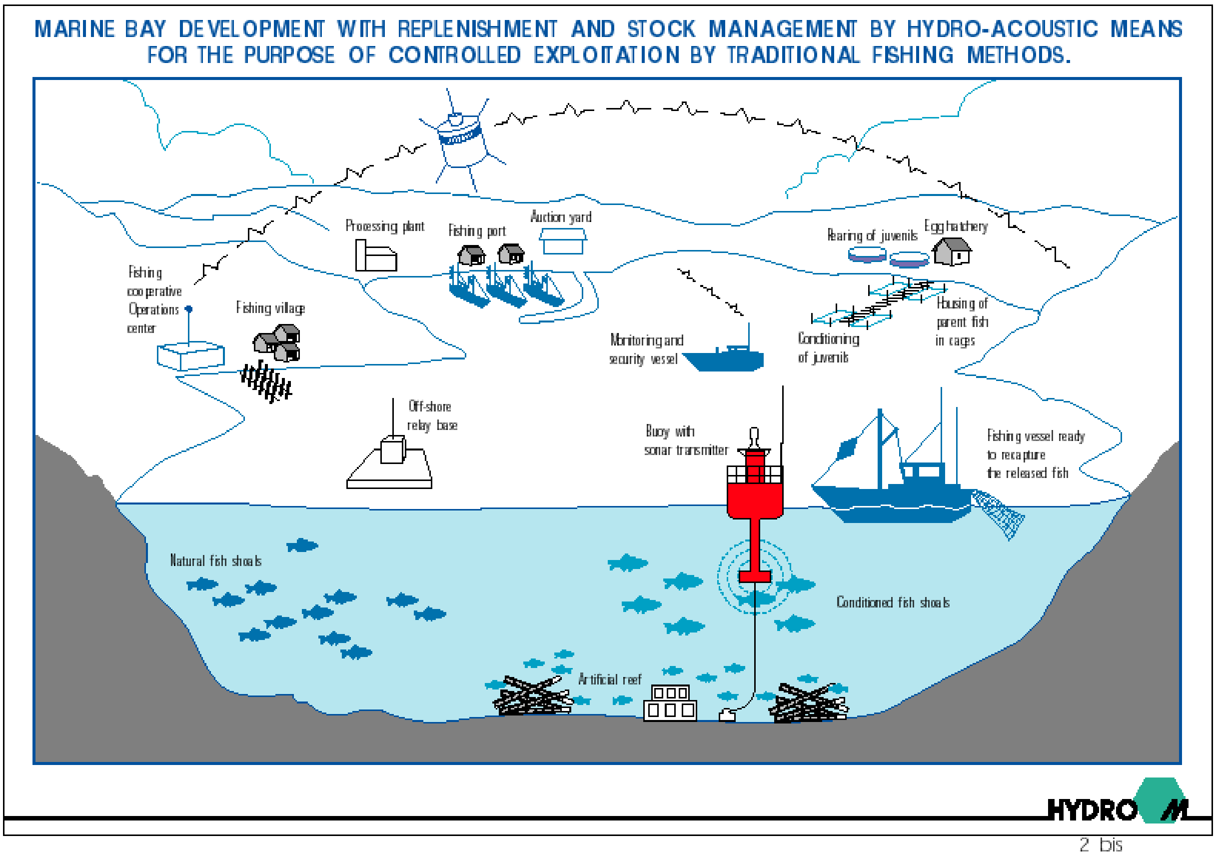

Figure 4.7: The FFFS concept promoted by the French company Hydro M.

This approach is still under development and has been limited to certain areas of France and Britain. Initial data suggests some success as both a replacement for traditional aquaculture and as a supplement to fisheries within inshore waters. However, a number of legal and environmental issues should be addressed:

- With fish being released into the sea, or open aquatic areas, they may be harvested by non-target fisheries, under the principle that everyone has the right to fish. The legal framework for this is complex and little understood but the onus is on the developer to prove ownership, otherwise anyone can fish the resource. As a supplement to fisheries this may be achieved in a controlled manner, in a managed fishery, but aquaculture systems would rely on recapturing a large number of the fish released to be economically viable.

- The other issue is that of the environment. Implementation of feeding stations releasing food into the natural environment would have to be carefully controlled otherwise there is likely to be large amounts of waste. In cage farms estimates of amounts of uneaten food range from 5 to 10% of that fed. It is likely to be considerably higher in a FFFS system. Care must also be taken in the stocks released. Many stocks have been selectively bred for aquaculture as being fast growing, high fecundity, rapid development and tolerant to a wide range of environmental conditions. These features would make these fish highly competitive in the wider environment. This can be offset by use of local stocks in local hatchery systems.

The concepts of FFFS are worthy of consideration as both alternative to aquaculture and supplement to fisheries but it is unlikely it will provide a solution to complex environmental and social issues mentioned.

5. Aquaculture for the 21st Century

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5. Aquaculture for the 21st Century

5.1 Forward projections for EEA aquaculture

Forward projections need to take account of likely changes in the capture fishery, and changes in population numbers, per capita fish consumption, and consumption preferences. However, whatever the composition and scale of fish consumption, an inverse price-quantity relationship is to be expected. A 'supply pyramid' can be described, with 85% of European fish products (by weight) priced below €2/kg (whole fish) at first sale value, with most of the remainder in the €2 - €5/kg range, which presently includes the bulk of farmed marine fish. Our baseline assumption is therefore that marine aquaculture is unlikely to produce at below €2/kg and that the present market structure will more or less be maintained with a 15% segment available to higher value marine aquaculture products. A shortage of < €2/kg cod and haddock from the fishery will most likely be substituted by other lower priced whitefish supplies, including those from tropical freshwater aquaculture, rather than from a corresponding increase in cod and haddock farming. Marine aquaculture is expected to expand to provide a greater variety of products (including cod and haddock to premium markets), to meet increases in demand through population growth, and to cater for greater seafood consumption by increasingly health-conscious populations.

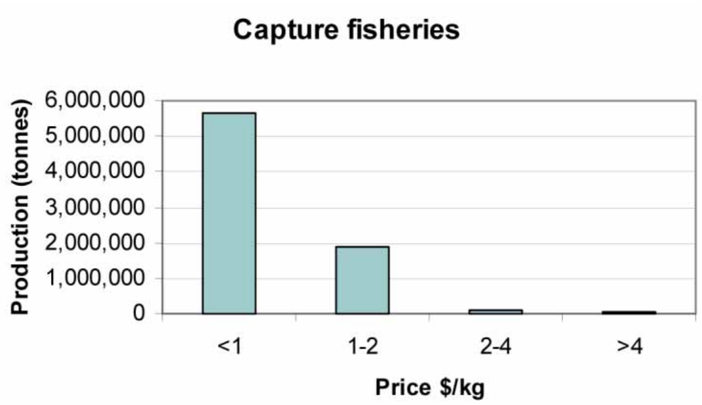


Figure 5.1: Volume:Price relationship for capture fisheries

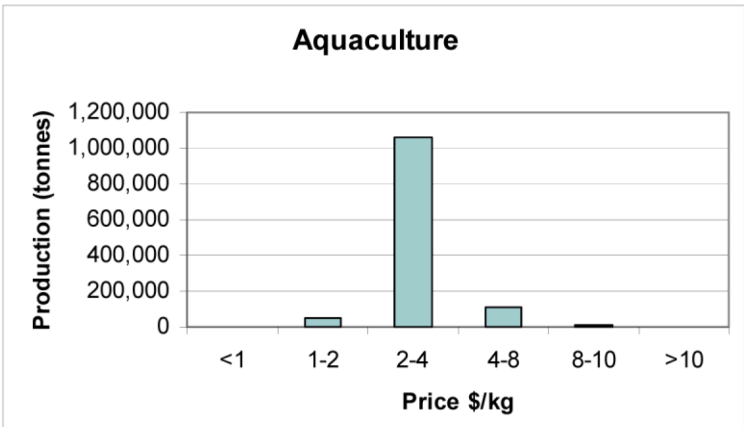


Figure 5.2: Volume:Price relationship for aquaculture

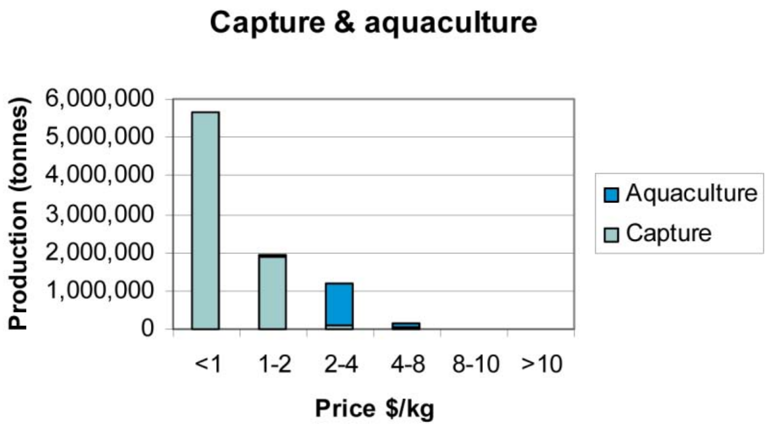


Figure 5.3: Volume:Price relationship for capture fisheries and aquaculture

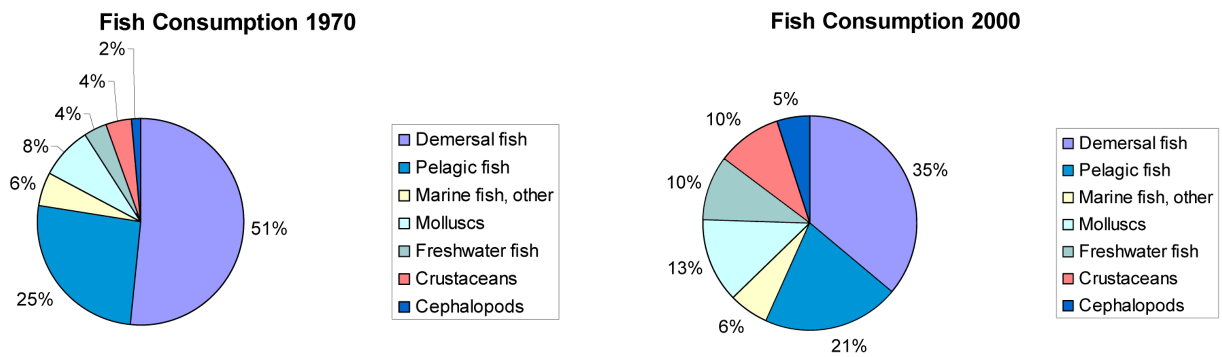


Figure 5.4: Altering patterns of EAA consumption indicated by higher proportions of molluscs, crustaceans and cephalopods in 2000 compared with 1970

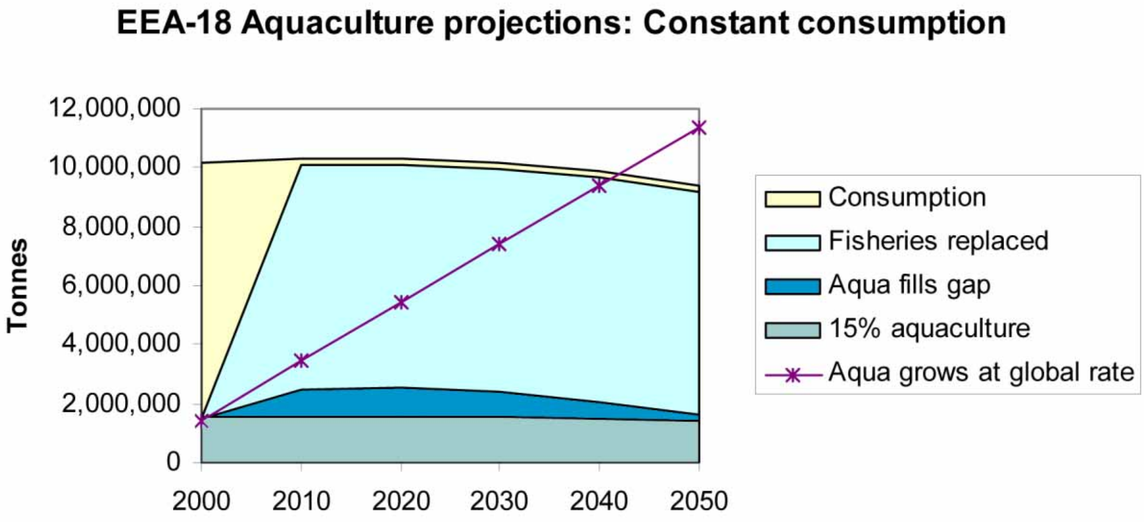
These assumptions suggest that EEA demand for marine aquaculture produce will rise by around 30,000 t over the next 30 years with no rise in consumption per capita, to as much as 700,000 t if per capita consumption of seafood continues the trend of the past 30 years.

If a more international view is taken, population growth and demand for seafood is projected to increase more rapidly outside of the EEA. This should present greater export opportunities for EU aquaculture producers and encourage higher growth than that suggested by EEA consumption alone. Such development would also help to address trade balance issues if the EEA were importing greater quantities of cheaper fish to compensate for declining domestic fisheries. However, markets are expected to remain competitive and supply sources from outside Europe may also become more important for the quality fish segment. For instance salmon production has expanded rapidly in Chile to the point where it is at or ahead of Norway's output levels[20]. New fast growing species such as Patagonian toothfish (*Dissostichus eleginoides*) and cobia (*Rachycentron canadum*) are also under development in the Americas, with potential to compete with European marine fish aquaculture.

If marine aquaculture in the EEA-18 countries were to track anticipated global trends in aquaculture production, a five-fold increase in output to around 7 million tonnes might be expected over the next 30 years (assuming partial fish oil and meal replacement). At this growth rate, marine aquaculture could more than fill any anticipated gap between fisheries supply and demand within the EEA, providing present catches are sustained.

20 Depending on estimates of current biomass

However, if all EEA-18 fisheries production were to cease within ten years, aquaculture would have to expand ten-fold to fill the supply gap. However, given existing pressures on coastal resources and relatively stringent and competitive procedures for allocation, other regions are more likely to pick up such production gains, as high costs of production for many species, and growing local output, are likely to limit Europe's competitive position outside its own markets. Where surplus European market demand exists, particularly for higher-value non-indigenous species, this in turn is likely to be more readily supplied through imports.



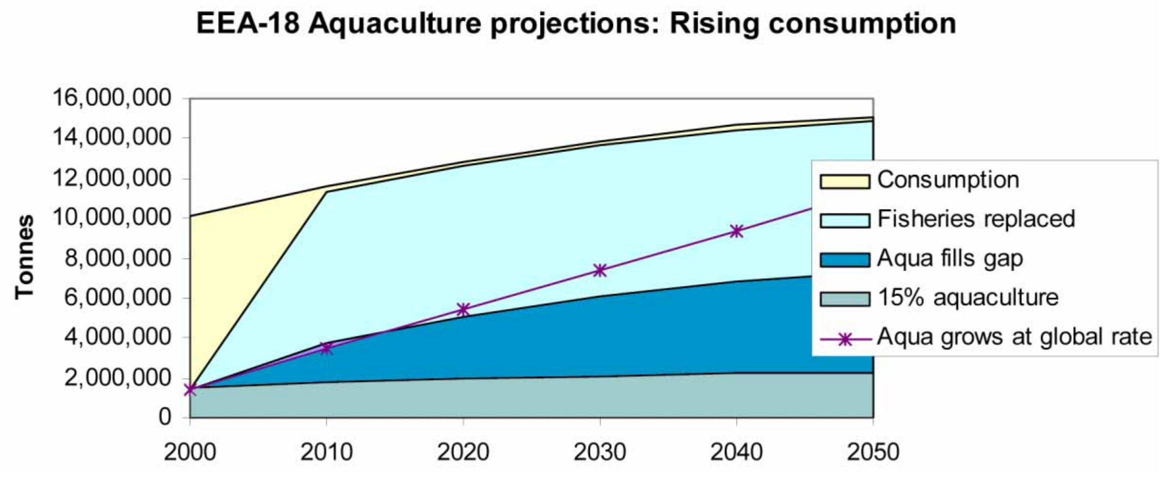


Figure 5.5: Forward projections for seafood consumption and aquaculture development in EEA-18 countries

Notes: The area charts above provide two scenarios based on (a) EEA-18 fish and seafood consumption remaining constant with population increasing slightly and then declining, and (b) EEA-18 fish and seafood consumption continuing to increase at the same rate as the last 30 years. The "Fisheries replaced" area represents the tonnage that would be required from aquaculture if all fisheries were to cease by 2010. The "Aqua fills gap" area represents the production that would be needed from aquaculture to fill the gap between existing supplies from the capture fishery and anticipated future demand. The "15% aquaculture" area indicates anticipated aquaculture production to fulfil the top 15% market segment. The line "Aqua grows at global rate" is based on FAO/World Fish Centre extrapolations of aquaculture growth rate and global demand and is not modified in the light of anticipated EEA-18 demand.

The most likely scenario on the basis of demand, is therefore that European marine aquaculture will expand over the near to mid-term future. Modifying factors will include regulatory constraints, technology developments and macro and micro economic cycles. Over 86% of EEA aquaculture is in marine or brackish water, and present expectations are that this sector will continue to be the main focus for investors. A realistic projection is therefore that the rate of growth in European marine aquaculture is likely to be somewhat below world averages. The main products will supply the premium 15-20% segment of the market with additional production exported to world markets. Growth however, is unlikely to be even. Expansion is thought to have slowed significantly over the past two years as low prices have halted large company investment programmes. Environmental protection measures may also have a constraining effect. However, if demand continues to grow and especially if capture fisheries decline, improved prices should encourage innovation and further expansion of production. We might therefore expect EEA country production to exceed 2 million tonnes by 2005, 3 million tonnes by 2020 and 4 million tonnes by 2040.

5.2 Challenges and solutions

With wild fisheries declining due to over-exploitation, aquaculture is considered by many to be the best and most logical solution for maintaining and even enhancing supplies of high quality seafood products. Sea fish are now the only major food sector that still predominantly relies on hunting rather than husbandry and cultivation. As seafarming is a relatively new industry, without a well-established and tradition place in rural and coastal affairs, it has naturally provoked a number of conflicts of interest, and concerns over environmental issues as the scale of the industry increases. Proper scientific scrutiny of these issues and best practices in environmental monitoring and management are supported by the industry and regulatory agencies. However, as with almost all human activity, zero impact is neither possible, nor necessarily desirable. At a time when the health benefits of marine food products, especially with respect to omega 3 oils, is increasingly recognised, and capture fisheries are also under scrutiny with respect to sustainability and environmental impact, the opportunity is presented to develop new models for managing marine resources, most likely involving greater emphasis on cultivation.

At present, fish farming provides only 2.7% of total marine finfish supplies. To substantially increase this share requires two key constraints to be addressed. Firstly the supply of marine fish oil and to a lesser extent fishmeal, is finite. Whilst present rates of growth can be sustained well beyond 2010, allowing at least a doubling of marine farmed fish production on the basis of current supplies, alternative suitable protein and lipid sources are needed for longer-term development. The second key constraint is the availability of suitable, and economically viable culture sites, having regard for environmental impacts. Opportunities are identified for the expansion of fish farming via offshore sites, on-shore pumped or recycled units, on-shore integrated pond systems and free-range farming. However, the constraints for each of these are considerable. Land-based farms are only likely to be viable for high value species (low volumes) unless energy and plant prices fall dramatically. Offshore farms are unlikely to be financially viable unless synergies are found with other activities (e.g. energy generation), or the cost of inshore farming increases substantially through regulatory effects. Removing aquaculture entirely from inner coastal zones is therefore economically difficult and technically uncertain. Developing coastal zone management plans that recognise a diversity of needs, that that emphasise sustaining healthy environments over strict conservation of existing conditions, is the most likely way forward for the immediate future.

Improvements in production efficiency are likely to be incremental, as most gains have already been captured. The key areas are likely to be in feed efficiency, the further reduction in mortalities due to disease, predators or escapees and better growth rates and utilisation of facilities. For marine fin fish, the greatest potential gains might be in the hatchery phase, where mortality rates are particularly high (although not as high as in nature). A key factor enabling salmon to be produced at lower prices has been its simple and cheap hatchery technology with relatively high survival rates. Marine species such as cod and haddock have culture potential, but for the foreseeable future will have much higher prices and hence more limited market scope, due to high hatchery costs. Selective breeding is likely to play an increasingly important role, although only GM technology offers realistic prospects of a major shift in production efficiency.

The goal of sustainable aquaculture development may not be easy to achieve given likely trade offs between social, economic and environmental considerations and between short and long term goals. The aquaculture industry is likely to remain relatively diverse with individual sub-sectors undergoing cycles of expansion, consolidation or stagnation. The solutions examined are by no means mutually exclusive, but relative economic performance will be the primary determinant of uptake, influenced by regulatory policies and consumer preferences. More comprehensive data collection concerning all aspects of aquaculture and coastal zone use combined with developing market traceability systems has the potential to form the core of an integrated information-rich approach to aquatic system management and better approaches to food safety and environmental protection.

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Selected Internet Information Sources

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Selected internet Information Sources

Status of aquaculture and fisheries and natural resource issues

http://www.fao.org/sof/sofia/index_en.htm
http://www.fishforall.org/background/pdf/fishforall_issue_paper.pdf
ftp://ftp.fao.org/fi/document/aqdeclar/declarat.pdf
http://www.iffo.org.uk/
http://213.121.208.4/pdfs/polstat/maritimeaquaculture.pdf
http://www.medobs.org/themes/aquaculture/aquaculture.pdf

Industry background

http://europa.eu.int/comm/fisheries/doc_et_publ/liste_publi/aqua2002_en.pdf
http://europa.eu.int/comm/fisheries/doc_et_publ/liste_publi/studies/aquaculture.pdf
http://www.aquamedia.org/
http://www.ssb.no/english/subjects/10/05/nos_fiskeoppdrett_en/
http://www.marlab.ac.uk/PDFs/ProdSurvey/survey2001.pdf
http://www.scottishsalmon.co.uk/
http://www.fishuk.net/ssfa/
http://www.shellfish.org.uk/
http://www.competition-commission.org.uk/reports/451nutreco.htm
http://www.intrafish.com/
http://www.fishupdate.com/
http://www.bim.ie/templates/fish_farming.asp?node_id=181
http://www.faosipam.org/
http://aquanic.org/
http://www.was.org/
http://www.easonline.org/

Major aquaculture and feed companies

http://www.nutreco.com/
http://www.marineharvest.com/
http://www.aquascot.uk.com/
http://www.stoltseafarm.com/
http://www.panfish.com/
http://www.ewos.co.uk/
http://www.biomar.co.uk/

Regulation

http://www.scotland.gov.uk/library5/environment/sfsa-00.asp
http://europa.eu.int/comm/dgs/fisheries/index_en.htm
http://www.marlab.ac.uk/
http://www.sepa.org.uk/
http://www.crownestate.co.uk/estates/scottish/fish/index.shtml
http://www.agf.gov.bc.ca/fisheries/regulation/aquaculture_regs.htm
http://www.seaweb.org/resources/sac/policy.html

http://www.intrafish.com/laws-and-regulations/report_bc/
http://www.marine.ie/scientific+services/monitoring/the+marine+environment/index.htm
http://www.epa.gov/fedrgstr/EPA-WATER/2002/September/Day-12/w21673.htm
http://www.wws.princeton.edu/~ota/disk1/1995/9554_n.html

Research & education

http://europa.eu.int/comm/fisheries/doc_et_publ/liste_publi/studies/synopsis/index.htm
http://www.aquaflow.org/
http://www.piscestt.com/
http://www.dfid.stir.ac.uk/
http://www.aquaculture.stir.ac.uk
http://www.akvaforsk.no/
http://genesis.ocean.org.il/main.htm
http://www.lifesciences.napier.ac.uk/maraqua/home.htm
http://www.tracefish.org/
http://www.sams.ac.uk/

Environmental issues:

http://www.scotland.gov.uk/cru/kd01/green/reia-00.asp
http://ressources.ciheam.org/om/pdf/c22/97605927.pdf
http://www.pewoceans.org/oceanfacts/2002/01/11/fact_22988.asp
http://www.fao.org/english/newsroom/news/2002/4140-en.html
http://www.fish.bc.ca/
http://www.wwf.org.uk/filelibrary/pdf/atlanticsalmon.pdf
http://www.nwfsc.noaa.gov/hab/biotoxins.htm
http://www.wws.princeton.edu/~ota/disk1/1995/9555_n.html

Offshore cages web sites:

http://www.farmocean.se/
http://www.fusionmarine.co.uk/
http://www-org.usm.edu/%7Eooa/index.htm
http://www.msicom.net/
http://www.oceanspar.com/
http://web.mit.edu/seagrant/advisory/cferprojects.html
http://www.sintef.no/publications/pro_eng_2.html
http://www.sadco-shelf.sp.ru/
http://www.itzasi.com/Tou/Tou1/EN/TUNAOFFSHORE/tunaoffshore.htm
http://www.poemsinc.org/platform.html

Tank-based and recirculation systems

http://aquanic.org/images/slides/ras.ppt
http://www.indoorfish.com/
http://www.aquafuture.com/
http://www.cnr.vt.edu/fisheries/extension/fishfarming/RecirculateAquaSys.html
http://aquanic.org/publicat/state/il-in/faq/ras_potential.htm
http://www.aesweb.org/pdfs/AES%20Special%20Session%202001.pdf
http://aquanic.org/publicat/state/il-in/ces/ces-240_real.htm
http://attra.ncat.org/attra-pub/aquaponic.html
http://www.aquasystems.co.uk/

http://www.pisces-aqua.co.uk/
http://www.drydenaqua.com/

Energy utilisation and optimisation

http://www.energywise.co.nz/subpdf/SouthernOceanFutures.pdf
http://www.anglingbc.com/davesreport/dave42.html
http://www.public.iastate.edu/~evo/nice.pdf
http://www.fao.org/docrep/T4470E/t4470e0l.htm
http://www.hawaii.gov/dbedt/ert/otec_hi.html
http://www.nrel.gov/otec/maricult.html
http://www.ocees.com/mainpages/Aquaculture.html
http://www.iowaagopportunity.org/ethanolmanual/integrat.pdf

Novel antifoulants

http://www.fpu-coatings.com/
http://www.naturesrepellent.com/abstract.html)
http://www.cleanseasco.com/

GM Technology

http://www.aquabounty.com/
http://www.bio.org/animals/faq.asp
http://www.sbs.soton.ac.uk/staff/nm/nm.htm

Annex I
Health Benefits and Risks Associated with Aquaculture Products

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Annex 1: Health Benefits and Risks Associated with Aquaculture Products

Health benefits

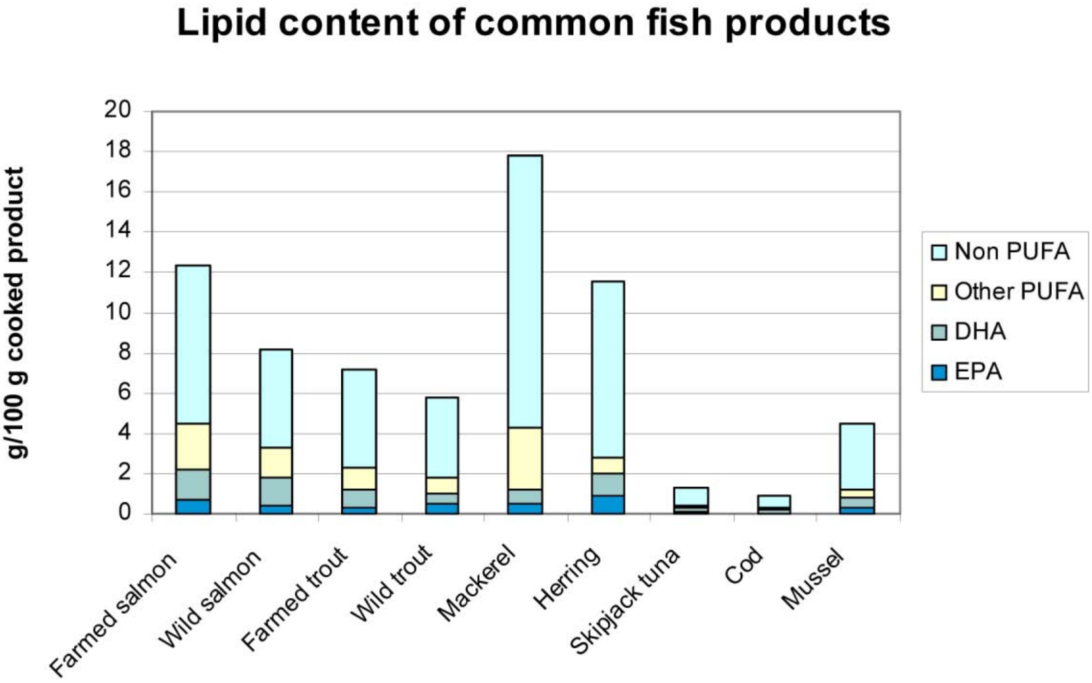
There is a considerable body of evidence that adequate intake of Omega-3 (or n:3) polyunsaturated fatty acids (PUFAs) is essential for human health. The most important members of the omega-3 group are considered to be eicosapentaenoic acid (EPA) with 20 carbon atoms and docosahexaenoic acid (DHA) with 22 carbon atoms, which are only available from marine sources (mostly fish, but also marine algae, including some seaweeds). Alpha-linolenic acid (ALA) with 18 carbon atoms is found in many plants (especially flax oil) and can be converted to EPA and DHA in the human body. However, this is a slow process that can be inhibited by high levels of omega-6 (n-6) lipids in the diet, or by some vitamin and mineral deficiencies. In average individuals only 15% of ALA is converted to EPA, and much less to DHA. For this reason, most medical authorities recommend the consumption of two portions of fish per week, one of which should be an oily fish[21] .

Table A1.1 Example recommendations

Advice	*Authority*	*Source*
Eat one portion of oily fish and one portion of white fish per week	Department of Health, Committee on Medical Aspects of Food Safety (COMA), 1994. Reviewed by Scientific Advisory Committee on Nutrition (SACN) 20/06/02.	"Nutritional Aspects of Cardiovascular Disease" Report on Health and Social Subjects No 46. S.3.7.3. p 17 London HMSO. & "Advice sought by FSA on the benefits of oily fish and fish oil consumption from SACN" http://www.doh.gov.uk/sacn/ sacn0212.pdf
Try to eat oily fish twice per week	British Heart Foundation	http://www.bhf.org.uk/hearthealth/ index.asp?secondlevel=78 &thirdlevel=350&artID=404
Eat a variety of fish at least twice per week and take additional fish oil supplements if suffering documented coronary heart disease	The American Heart Association	http://www.americanheart.org/ presenter.jhtml?identifier=4632

Recent research is focusing less on absolute levels of n-3 PUFA consumption and more on the ratio between n-3 and n-6 PUFAs and even between individual fatty acids. Western diets tend to be high in n-6 PUFAs (e.g. from margarine, vegetable oils and many processed foods) and therefore have a high n-6:n3 ratio. Increasing n-3 and in some cases decreasing n-6 PUFA consumption is therefore a common dietary recommendation. Marine fish represent the most accessible source of n-3 PUFAs for most consumers, but can be deterred from increased consumption by factors such as price, availability, taste and risk of contaminants (see discussion below).

21 A Fish Inter-Committee Sub-Group (FICS) was established in June 2003 to review this advice. The sub-group brings together members from COT and SACN (http://www.sacn.gov.uk/fish.htm)



Source: USDA National Nutrient Database for Standard Reference Release 15

Table A1.2 n-3 PUFA content of selected fish products

	Total fat (g/100g of dry cooked edible meat)	Total PUFA (g/100g)	PUFA % of total fats	EPA (g/100g)	EPA (% of total fats)	DHA (g/100g)	DHA (% of total fats)
Atlantic salmon (farmed)	12.35	4.43	35.84	0.69	5.59	1.46	11.80
Atlantic salmon (wild)	8.13	3.26	40.09	0.41	5.04	1.43	17.59
Rainbow trout (farmed)	7.20	2.33	32.36	0.33	4.64	0.82	11.39
Rainbow trout (wild)	5.82	1.83	31.46	0.47	8.04	0.52	8.93
Mackerel	17.81	4.3	24.14	0.50	2.83	0.70	3.92
Herring	11.59	2.74	23.60	0.91	7.84	1.10	9.53
Skipjack tuna	1.29	0.40	31.01	0.09	6.98	0.24	18.60
Cod	0.86	0.29	33.72	0.004	0.46	0.15	17.44
Mussel	4.48	1.21	25.02	0.28	6.16	0.51	11.29
Salmon oil	100.00	40.32	40.32	13.02	13.02	18.23	18.23
Cod liver oil	100.00	22.54	22.54	6.90	6.90	10.97	10.97

Source: USDA National Nutrient Database for Standard Reference Release 15

Farmed salmon and trout are among the best sources of dietary EPA and DHA at the present time, due to the high inclusion level of quality marine fish oils in modern feeds. Increased use of vegetable derived oils in aquaculture feeds may reduce the absolute EPA and DHA content of the fish, although feeding a high marine fish oil diet during the final phase of growout may reduce this effect.

Alternative dietary sources of n-3 PUFAs are under investigation, for instance from microalgae or genetically engineered plants and bacteria. In the USA the North Central Region Association of Agricultural Experimental Station

Directors have a multi-regional project on this theme with a useful discussion of the issues at the following web site. http://www.lgu.umd.edu/project/outline.cfm?trackID=2294. However, alternatives sources are either not yet available or are considerably more expensive than marine fish. A more accessible review of the possible health benefits of fish oils is available at http://www.oilofpisces.com/, although it must be noted that this is an independent site that promotes alternative therapies and nutritional supplements. Nevertheless it provides a clear overview of the claims that have been made for omega-3 fatty acids and an introduction to some of related scientific literature. A briefer summary of reported effects, with example sources is given below.

Table A1.3 Example references

Reported effect	*Source details*	*Reference details*
A consumption of 2-4 g of fish oil per day can decrease triglyceride levels by 25% or more and significantly lower the risk of cardiac events (heart attack) and associated mortality	American Association of Clinical Endocrinologists Medical Guidelines for clinical practice for the diagnosis and treatment of dyslipidemia and prevention of atherogenesis	http://www.aace.com/clin/guidelines/lipids.pdf
Women who eat fish two or more times per week have a 48% lower risk of ischemic stroke than women who eat fish less than once per month	Nurses Health Study published in the Journal of the American Medical Association and cited by the Harvard Medical School Family Health Guide	http://www.health.harvard.edu/fhg/Darchive/diseases.501.shtml#fish
Low birth weight and premature birth risk reduced if women eat fish during early pregnancy	Statens Serum Institut, Copenhagen – study of 9000 women	British Medical Journal 324 p 447 cited in New Scientist www.newscientist.com/news/news.jsp?id=ns99991964
Asthma attacks may be reduced by eating oily fish, incidence in pre-school children may be influenced by monther's consumption of oily fish during pregnancy	Research at University of Cambridge and University of Aberdeen (Ongoing)	http://news.bbc.co.uk/1/hi/health/2547009.stm http://www.asthma.org.uk/help/research02.php
Fish consumption (or fish oil supplements) can reduce the symptoms of rheumatoid arthritis	Validation of a meta-analysis by the University of York NHS Centre for Reviews and Dissemination	http://nhscrd.york.ac.uk/online/dare/960059.htm
Omega-3 fatty acids (as found in fish oil) help protect against some cancers, especially breast and colon cancers	e.g. Maillard et al (2002) Int. J. Cancer 98 (1): 78-83 and Murray et al (2002) J. Cell Biology 157 (6).	http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=11857389&dopt=Abstract http://www.altmedicine.com/Article.asp?ID=3387
Omega-3 fatty acid supplements or eating oily fish may reduce symptoms in mental disorders such as depression, bi-polar disorder and schizophrenia	Various, including Cochrane Review, The Cochrane Library; Stoll et al 1999 Arch Gen Psychiatry 56, (May) 407-12 and 413-13	http://cebmh.warne.ox.ac.uk/cebmh/elmh/schizophrenia/tx/other/fishoil2.html#effects http://news.bbc.co.uk/1/hi/health/760382.stm http://www.update-software.com/ccweb/cochrane/revabstr/ab001257.htm http://archpsyc.ama-assn.org/issues/v56n5/toc.html
Omega-3 fatty acids from fish oils may provide benefits for cystic fibrosis sufferers	Beckles Willson et al 2003, The Cochrane Library & others	http://www.cochrane.org/cochrane/revabstr/ab002201.htm http://news.bbc.co.uk/1/hi/health/469032.stm
Diets with a low n-6:n-3 ratio appear to have a beneficial effect on bone mineral density and hence help prevent osteoporosis	Albertazzi & Coupland, 2002, Maturitas 42 (1): 13-22	http://dx.doi.org/10.1016/S0378-5122(02)00022-1

Whilst n-3 lipids appear to be of greatest significance for Western diets, fish also contribute to a healthy and balanced diet in other ways, as they have a high protein content, including all essential amino acids, are a good source of vitamins A, D and B complex, and can also provide valuable minerals such as iodine, calcium, iron, zinc and selenium.

Potential health risks

Whilst seafood clearly plays a major role in promoting health, there are a number of hazards that also need to be considered. These include the contamination of seafood with pathogenic bacteria or viruses, the accumulation of natural biotoxins in seafood, the accumulation of industrial pollutants in fish and seafood, contamination through use of therapeutic compounds in aquaculture and potential risks introduced through specific ingredients in compounded fish diets in aquaculture.

Bacterial and viral contamination

At a global level, this is perhaps the issue of greatest concern. Human pathogens are discharged in untreated or poorly treated sewage near to shellfish culture areas, leading to accumulation in the animals. Subsequent consumption of raw or poorly cooked shellfish can pass on the disease agents. Alternatively, poor hygiene in seafood processing plants can allow product to be contaminated with human pathogens. This issue has been widely addressed in many parts of the world (including Europe) through classification of waters suitable for shellfish culture, and strict hygiene controls throughout the production and processing chain.

Contamination with natural biotoxins

After bacterial and viral contamination, the accumulation of natural biotoxins, mainly in shellfish, is the next most serious health issue. These mostly relate to the occurrence of harmful algal blooms (HABs) where shellfish ingest the microalgae (mainly dinoflagellates) and accumulate the biotoxin that they contain. The shellfish are often unaffected, but subsequent human consumption can lead to serious sickness and even death. These toxic effects are classed medically as paralytic, neurotoxic, amnesic, or diarrhetic shellfish poisoning (PSP, NSP, ASP, and DSP respectively). Ciguatera fish poisoning (CFP) is similarly caused by biotoxins produced by epibenthic dinoflagellates attached to surfaces in many coral reef communities that are transferred through the food chain from herbivorous reef fishes to larger carnivorous, commercially valuable finfish.

The issue is increasingly addressed through improved shellfish monitoring programmes and increasing research into the causes of HABs, including any possible linkages with aquaculture (see Scottish Executive Report "Review and synthesis of the environmental impacts of aquaculture", 2002, for further discussion of this point). Overall, the close management and monitoring of aquaculture operations reduces the risk of contaminated product reaching the market.

Dioxin contamination

Dioxins are a large group of chemical substances[22] that are mostly formed during combustion processes and also as trace contaminants in the synthesis of some chemicals and other industrial processes (COT, 2002). Of these, 17 are considered biologically active and are thought likely to be carcinogens and have other adverse physiological effects. A similar class of compounds are the dioxin-like poly-chlorinated biphenyls (PCBs), which were manufactured for a range of industrial applications between the 1930s and 1970s. Of over 200 PCBs, only 12 show dioxin-like biological activity (COT, 2002).

These compounds have been released into the environment over a long period and are now commonly detected throughout the food chain, with the highest levels found in the fats of carnivorous animals, especially marine fish. As much intensive aquaculture throughout the world uses artificial diets where the main protein and lipid source comes from marine fishmeal and fish oil, these products are at risk of contamination. The level of contamination depends on the source of the fishmeal and especially oil, as northern sources (The Baltic &

22 There are two main groups of dioxins: The polychlorinated dibenzo-*p*-dioxin (PCDD) (75 compounds) and the dibenzofuran (PCDF) group (135 compounds).

North Sea) tend to be more heavily contaminated than southern sources (e.g. Pacific sources from Chile and Peru).

Dioxins and PCB-like dioxins are complicated to analyse and quantify from environmental samples as 29 substances (17 dioxins and 12 dioxin-like PCBs) within this group have to be discriminated, detected and quantified as only a few of them may pose significant risk to health. The analytical method is both time-consuming and very expensive. To enable better comparison and to assess risk, the World Health Organisation (WHO) coordinated a panel of experts to develop a method to calculate total toxic risk of mixtures of dioxins and dioxin-like substances. This measure is represented by "total dioxin like toxic equivalence" (TEQ), enabling the relative toxicity and risk of dioxin levels to be compared directly. Fish meal and other commonly used foodstuffs are compared using their TEQs in Table A1.4

Table A1.4: Dioxin levels in feed materials[23]. Data expressed as ng WHO-TEQ per kg dry matter

Food material	Mean	Range
Cereals and seeds	0.1	0.01-0.4
Vegetable oil	0.2	0.1-1.5
Meat and bone meal	0.2	0.1-0.5
Animal fat	1	0.5-3.3
Fish meal Pacific	0.14	0.02-0.25
Fish oil Pacific	0.61	0.16-2.6
Fish meal Europe	1.2	0.04-5.6
Fish oil Europe	4.8	0.7-20

Levels vary but it can be clearly seen that the mean values for fishmeal and oil are generally higher than for the other foodstuffs. In particular, levels within European derived fishmeal are 5 to 20 times higher than vegetable oil and 1 to 5 times higher than animal fat. This may pose significant problems to aquaculture because of the potential for transfer to the cultured species and hence into food products.

The UK Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT) reviewed available data in 2002 and revised its guideline on the tolerable daily intake (TDI) of dioxins and dioxin-like PCBs downwards from 10 pg/kg bw/day to 2 pg/kg bw/day. For an average adult of 70 kg, this is 140 pg/day or 980 pg/week. Recent information on levels of contamination in farmed salmon (Jacobs *et al*, 2002; Lindström *et al*, 2002; Food Safety Authority of Ireland, 2002) suggests average levels are between 0.65 and 4.0 WHO-TEQ pg/g. For a typical portion of 130g of salmon, this suggests an exposure of between 85 and 520 pg. Most advice has therefore recommended eating one portion of fatty fish such as salmon per week as safe for adults, and indeed the benefits of omega-3 fatty acids in the diet are likely to far outweigh any risk from dioxin contamination at this level. There may be more risk for young children and especially to babies during pregnancy or breast feeding, although omega-3 fatty acids (especially DHA) are particularly essential at this time (e.g. Willatts *et al*, 1998; Smuts *et al*, 2003).

Overall exposure to dioxins and dioxin-like PCBs is falling in the UK. Recent figures suggest an average of 1.8 pg/kg/day with the 97.5% of consumers below 3.1 pg/kg/day. This is only a quarter of the exposure measured in 1982 (COT, 2002). EC regulations introduced in 2001 for implementation in 2002 set limits for dioxins in food products and animal feeds, but due to lack of data did not include dioxin-like PCBs. It is anticipated these will be included in the legislation by 2006, following a review of the limits no later than 31 December 2004. The current regulations are:

23 Data from the Report of the Scientific Committee on Animal Nutrition (SCAN) of the EC, November 2000.

Table A1.5: EC Legislation on dioxins

Council Regulation 2375/01/EC amending Council Regulation EC 466/2001: Setting maximum levels for certain contaminants in foodstuffs	Muscle meat of fish and fishery products (for human consumption)	4 pg WHO-PCDD/F-TEQ/g fresh weight (Action level at 3 pg/g)
	Fish oil for human consumption	2 pg WHO-PCDD/F-TEQ/g fat
Council Directive 2001/102/EC amending Council Directive 1999/29/EC: On the undesirable substances and products in animal nutrition	Feeding stuff for fish (e.g. formulated diets)	2.25 ng WHO-PCDD/F-TEQ/kg
	Fish and other aquatic animals and their byproducts (e.g. fishmeal)	1.25 ng WHO-PCDD/F-TEQ/kg
	Fish oil for inclusion in compounded diets	6 ng WHO-PCDD/F-TEQ/kg

Note: the units ng/kg and pg/g are equivalent (parts per trillion)

Available data suggests that farmed salmon have average dioxin levels well below these limits (below 25% of the limit was found by the Food Safety Authority of Ireland, 2002). However, the industry is making considerable efforts to further reduce the levels of contamination by (a) sourcing feed ingredients that have lower levels of contamination (e.g. fishmeal and oil from the southern rather than northern Hemisphere), (b) reducing the proportion of fishmeal and oil in the diet by substitution with suitable terrestrial proteins and oils, and (c) exploring the option of treatment processes to remove contaminants from fish oil. All of these options have significant cost and/or environmental implications. An associated issue is access to reliable and lower-cost analysis for dioxins and dioxin-like PCBs. A study by Lindström *et al* (2002) found variations of up to 50% between laboratories in analysis results. The development of more direct measurement methods using bio-assay approaches (e.g. CALUX – Chemical-activated luciferase gene expression) to directly measure TEQ, may not improve on accuracy, but offers the possibility for more routine screening of materials.

Contamination by heavy metals

As with dioxins, heavy metals can also be present in the aquatic environment, due to natural geological reasons (volcanic activity, or the erosion of earlier deposits by streams and rivers), and industrial pollution. Greatest attention has been given to mercury, as this is both highly toxic and is especially prone to bioaccumulation. However, an excess of other heavy metals such as lead, cadmium, arsenic, antimony, barium, and chromium, can also pose a risk to human health.

Table A1:6: Heavy metal contaminants and associated health risks

Metal	Health risks	Maximum permitted level in fish products (EC) (mg/kg wet weight)
Mercury	Is most toxic in the form of methylmercury, which is produced by the action of microorganisms in the aquatic environment. Acute poisoning causes pharyngitis, gasteroenteritis, vomiting, nephritis, hepatitus, and circulatory collapse. Chronic poisoning may cause liver damage, neural damage, and congenital malformations.	0.5 (most species), 1.0 (specified species including tuna, swordfish, sailfish, shark, marlin etc.)
Cadmium	Interferes with the protein metallothionein, which normally binds excess essential metals to render them unavailable. This disrupts the body's ability to regulate zinc and copper concentrations.	0.05 (most species), 0.1 (specified species including tuna), 0.5 (crustaceans), 1.0 (bivalve molluscs and cephlapods)
Lead	Can accumulate in children's bones through substitution for calcium but may later be released if calcium intake increases, leading to toxic effects that include nephrotoxicity, neurotoxicity, and hypertension	0.2 (most species), 0.4 (specified species including tuna), 0.5 (crustaceans), 1.0 (Cephlapods), 1.5 (bivalve mollucs)
Arsenic	Can cause vomiting, diarrhea, and cardiac abnormalities	
Chromium	Can cause respiratory and dermatological problems	

*Adapted from **http://h2osparc.wq.ncsu.edu/info/hmetals.html** with EC limits from Commission Regulation (EC) 466/2001 with amendments from Commission Regulation (EC) 221/202.*

Metals such as cobalt, molybdenum, vanadium, strontium, zinc, copper, iron and manganese are essential to health in trace amounts, and under normal circumstances uptake is regulated by the body to prevent accumulation. Higher levels of these metals can therefore be tolerated without adverse health risks.

Monitoring for heavy metal contamination is technically easier and therefore cheaper than monitoring for dioxins. However, patterns of contamination may be complex as different species appear more susceptible than others to contamination (presumably due to different uptake and elimination rates), there may be seasonal fluctuations, and also differential accumulation within body tissues. The latter may depend on the molecular form and hence biological activity of the metal, and chemical and physiological interactions due to multiple contaminants may also play a role.

Heavy metal contamination is most commonly reported from capture fisheries, especially contaminated freshwaters and some industrialised coastal zones. Greatest attention has been given to mercury, which is a serious and persistent problem in some areas, including some of the lakes and rivers of North America. The worst documented case of mercury contamination occurred in Minamata, Japan, where over 1000 people died and more than 2000 suffered serious symptoms associated with mercury poisoning due to industrial discharges between 1930 and 1970. A recent survey of mercury contamination in fish products by the UK Food Standards Agency (FSA, 2002) resulted in the advice that women who are pregnant or who may become pregnant, infants, and children under the age of 16 should avoid eating shark, swordfish and marlin, which are all top-level marine carnivores. Other consumers are advised to limit consumption to no more than 1 portion per week[24]. The same survey found farmed fish and shellfish to have some of the lowest levels of mercury contamination.

Heavy metal contamination should be less of an issue for aquaculture, where water quality and feeds are under stricter control. Although problems may exist in countries where little monitoring is carried out and contaminated water sources or feeds may be used (e.g. see Mansour & Sidky, 2002 & Hashmi, M.I, Mustafa, S. & Tariq, S.A., 2002). There is also potential for heavy metal contamination from inappropriate aquaculture equipment (especially zinc and copper) or chemical treatments (e.g. copper-based antifoulants or algal treatments). However, since heavy metal contamination can also often affect the cultured species, problems are more likely to be detected at an early stage. A number of water treatment technologies exist that can reduce heavy metal concentrations in a water supply, although locating projects to avoid contaminated supplies is the preferable and more economic option.

Therapeutant contamination

The use of therapeutants in aquaculture is generally regulated, most strictly in Europe and North America. In the UK, fish products are randomly monitored for therapeutant residues by the Veterinary Medicines Directorate and Food Standards Agency, and action taken if permitted levels are exceeded. Similar programmes are conducted within Europe, resulting for instance in wide ranging bans on seafood imports from China and a number of other Southeast Asian countries in 2001 – 2002 due to the detection of residual levels of the banned antibiotic chloramphenicol. The issue is shared by the farmed livestock sector and concerns veterinary treatments such as antibiotics, antiparasitics and vaccines. There appears to be little clinical evidence that such contaminants have harmed human health, but the risk of sub-clinical effects is taken seriously and assessed on a case-by-case basis by the Veterinary Medicines Directorate in the UK (See http://www.vmd.gov.uk/ and especially http://www.vmd.gov.uk/general/publications/liaisonmeeting.pdf)

Of more recent concern has been the detection of residues of malachite green and leucomalachite green in a small number of samples of farmed trout and salmon in the UK (http://www.vmd.gov.uk/mavis/publications/Mavis47.pdf), with similar findings in Chile. These compounds were banned for use in UK fish farming in June

24 See Harris H.H, Pickering, I.J., and George, G.N. 2003. The Chemical Form of Mercury in Fish. Science Aug 29 2003: 1203 for discussion on the way in which the mercury is bound in the fish flesh possibly reducing risk.

2002 (following European and American legislation), due to established carcinogenic properties, although it was anticipated that residues would be detected into 2004 due to the persistence of the compound in fish flesh. The ban has been widely supported by the aquaculture industry, despite limited and more costly alternative antifungal treatments at present. Further progress in eliminating these residues is therefore anticipated.

Feed pigments

The carotenoid pigments Astaxanthin and Canthaxanthin are often used within artificial diets of intensively produced fish and shellfish, as a replacement for the same pigments which naturally occur in the diets in the wild. These pigments are fully approved for use in the EU and UK for inclusion in salmon diets and are one of about 600 naturally occurring carotenoid pigments found in animals and plants. In the aquatic environment, astaxanthin is biosysnthesised by microalgae or phytoplankton and passed up the food chain. The use of astaxanthin and canthxanthin in artificial foods is therefore to mirror the diet of wild fish and provides colour and anti-oxidant properties. These pigments are considered more than simply "cosmetic colourants". As antioxidants they protect against effects of oxygen-free radicals and may be seen as important to good fish health, and thus an essential dietary component.

The use of canthaxanthin in artificial fish diets, certified as E161g has recently been subject to review, as at high dietary inclusion levels (e.g. in artificial suntan pills) have been found to cause damage to eyesight. At present the maximum content for salmon and trout diets allowed by the EC (under Directive 70/524) is 80 mg/kg feed, and mixed with astaxanthin so that the total concentration does not exceed 100 mg/kg in the complete feedingstuff (Food Standards Agency, 2002). The EC Scientific Committee on Animal Nutrition (SCAN) reviewed the present levels and concluded that consumers of high amounts of farmed fish may exceed the acceptable daily intake (ADI) for canthaxanthin (which is up to 0.03 mg/kg body weight). SCAN recommended that a more suitable maximum level in salmonid feeds would be 25 mg/kg feed, a value which would be generally be exceeded at present usage levels. This recommendation has now been adopted (January 2003) and is due for implementation under national legislation by the end of 2003. However, the legislation will reportedly only apply to EU producers, placing them at a competitive disadvantage with respect to the larger proportion of imported salmon (e.g. from Norway, Faeroe and Chile), which will not have to apply the same regulations.

Again, as with food contaminants, the benefits of consumption by fish by consumers have to be weighed against the potential risks. Typically fish fed artificial diets containing canthaxanthin is reported to contain around 5 mg/kg (industry derived data), so a 70 kg adult could consume considerable amounts of salmon (300-420 g) every day without exceeding the ADI. Therefore the usual dietary intake of fish by adults is very unlikely to exceed European ADI levels.

Summary

There are well-documented benefits to the moderate consumption of seafood in general, and oily fish in particular as part of a well-balanced diet. There are a number of potential health risks associated with fish and seafood consumption, some of which have clear expression in clinical symptoms, whilst others can only be considered as risk factors that may contribute to more complex ill health problems over a longer time period. Farmed fish, especially in Europe, has a good record with respect to acute clinical food safety issues, whilst shellfish farming can also be shown to improve food safety standards through better monitoring and management. Aquaculture does entail a somewhat different set of risks compared with wild-caught product, but to date there is little clinical evidence that these are of major significance. As far as possible a precautionary approach is being taken by the responsible authorities and the trend towards greater product traceabilility in aquaculture will add further assurance from the perspective of food safety.