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Managing to harvest? Perspectives on the potential of aquaculture

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Aquaculture has been one of the most rapid and technically innovative of food production sectors globally, with significant investment, scientific and technical development and production growth in many parts of the world over the past two decades. While this has had a significant effect on the global supply of aquatic food products and an important impact in rural and urban food supply and employment in many developing economies, growth and increasing internationalization has not been without concern for natural resource use, environmental impact and social disruption. The expectations for production and diversification are now significant and while the scientific and technical means are already available to meet much of the intended targets, practical constraints of investment, profitability, resource access and system efficiency are likely to become far more important constraints for the future. This review offers a contemporary perspective on the ways in which the sector might develop, its interactions with constraints and the strategies that may be required to ensure that future development is both positive and sustainable.

Keywords: aquaculture; fisheries; resources; development; markets

1. INTRODUCTION

(a) *Global trends of development*

According to the World Fish Centre[1] and IFPRI[2] (Ahmed & Delgado 2000; Delgado *et al.* 2002, 2003) global *per capita* fish consumption has doubled over the past 50 years, and production would need to double again to meet projected demand over the next 25 years. However, supply from capture fisheries is at best static, with most wild stocks already heavily depleted, overfished or fully exploited. Driven by technical development, market opportunities and investment incentives, aquaculture production has increased 10-fold over the past 30 years and in 2000 supplied *ca.* 27% of fish, crustacean and mollusc products (35.5 mt), although only 2 mt were marine fishes, only 2.7% of total marine fish supplies (4.8% of marine fishes for human consumption; FAO 2002*a*,*c*). Global output owes much to China, whose reported production by volume accounts for 32% of the world total. In China also, by 1999, the balance of production had shifted from fisheries (17.8 mt) to aquaculture (22.8 mt). Other major producers are Japan, India, the United States, the Russian Federation and Indonesia, while European production represents just 3% by volume (figure 1; table 1).

In Asia, the dominant source of supply, much of the production is from traditionally based pond aquaculture integrated into wider farming systems (e.g. Song 1999). 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 using ponds, tanks and cages. Figure 2 outlines the main product groups, showing the dominance of freshwater fishes, the importance of molluscs and aquatic plants and within the smaller marine sector, the dominance of salmon, whose culture has tended to lead much of the current technical and investment drive in the last decades.

The estimated first sale value of cultured fish and shellfish in 2000 was *ca.* US$56 billion, of which fish represented US$31.5 billion and shellfish including shrimp US$18.8 billion. By volume, 58% was from fresh/inland waters, 6% from brackish water (mainly shrimp)[3] and 36% from marine waters, of which 82% is related to molluscs and only 15.6% to fish (1.15 mt of salmon and trout and 856 600 t of marine fishes), although accounting for 40% of value. Coastal (marine plus brackish water) aquaculture is growing more quickly than inland aquaculture, albeit from a lower base (FAO 2002*a*,*c*).

(b) *Trade and internationalization*

The global biogeography of aquatic resources has ensured long-standing and varied patterns of consumption and trade throughout history (Young & Muir 2002*a*). In the fisheries sector more widely, international trade has both flourished and declined as stocks become exploited and markets are developed for them, technology change in catching and processing providing increasing scope for storage, value development and longer supply routes. Aquaculture technologies have in turn created new opportunities in specific environments and global locations (Paquotte 1998), with modern transport, notably by air, enabling a complex logistics network to be created, with far greater global movement of product and an increased process of commoditization of an otherwise rather specialized product. Thus, for farmed Atlantic salmon, over 50% of global demand is supplied from Norway alone, much of which is marketed fresh or chilled. The resultant pattern of

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One contribution of 15 to a Theme Issue ‘Fisheries: a future?’.

trade flows is also defined by the distribution of those willing and able to pay and those still having fish resources to trade. However, if marketing is to contribute to the benefits to be attained by suppliers and consumers, it is necessary to understand the main international markets and their respective sources of supply (Young & Muir 2000, 2002*a*).

Dependence on international trade is widely evident and in 1996, in fishery products, 195 countries reported exports, and 180 recorded imports, and the total value of exports was estimated to have risen from US$17 billion to US$52.5 billion from 1985 to 1996. This was initially associated with low-value commodities such as fishmeal, reducing value per volume, but more recently has tended towards increased value owing to higher prices, with a much greater share being taken by aquaculture production. Developing countries recorded a trade surplus of US$16.6 billion in 1997; from which, by value, more than half of fishery export derives, mainly imported into developed countries and increasingly influenced by aquaculture. However, though Thailand was the leading world exporter between 1993 and 1996 (US$3.4 billion), based primarily on high-value farmed shrimp production, Norway's growing exports of farmed salmon gave it the lead by 1997, and this in turn may well become eclipsed by aquaculture production from Chile. With imports valued at US$15.5 billion in 1997, Japan was the leading importer while the United States accounts for *ca*. 10% of world fish imports. Together with the European Union (including intra-EU trade), these three blocs imported 75%, by value, of internationally traded fishery products (FAO 1999). Within these trade flows, aquaculture occupies similar positions, though trade is even more associated with the export of higher-value products to more prosperous markets, with correspondingly significant trade imbalances. In many cases, this leads, in poorer countries, to a significant distinction between higher-value, commonly more intensive and resource-demanding processes serving export markets, and much simpler, lower value domestic production.

2. SYSTEMS, PRODUCTION STAGES AND RESOURCE USE

Aquaculture is commonly defined by area-based yield levels, in terms of extensive and intensive, similar in concept to equivalent terms in agriculture. This also offers useful analogies with aquatic ecosystems, related to the range from oligotrophic to eutrophic systems, corresponding to low and high nutrient levels and productivity, though in more artificially controlled systems, nutrient and energy densities extend well beyond eutrophic levels. In a broad continuum, extensive systems are closest to natural fisheries, requiring minimal inputs and offering relatively low yields—typically 100–300 kg ha^{-1} yr^{-1}, while intensive systems require a large amount of inputs to maintain an artificial culture environment, with high yields, of 10–200 kg m^{-3} yr^{-1} (100–2000 t ha^{-1} yr^{-1}, depending on water depth). Between these extremes are varying degrees of semi-intensive aquaculture, where definitions are less distinct (Muir 1995). One of the simplest is that used by FAO, where:

(i) extensive aquaculture does not involve feeding of the culture organism;
(ii) semi-intensive aquaculture involves partial feeding through fertilization and/or feeds;
(iii) intensive aquaculture is where the culture species is maintained entirely by artificial feeding.

A further area of description is that of enhanced or culture-based fisheries, where hatchery reared stocks are introduced into open water bodies—lakes, lagoons, rice-fields, river floodplains, inland or coastal enclosures, reefs, or open sea, subjected to various levels of management, replacing or more often supplementing indigenous stocks in these water bodies. Here, yields may be defined as much by fishing practice as by productivity, and more conventional aquaculture input–output relationships tend to be less applicable. Finally, distinctions can be made between production systems based on their degree of internal recycling of productive inputs (Reta Mendiola 1999). Thus in extensive and semi-intensive systems a large part of productivity is internally generated, with incident water and energy the primary driving elements. This can further be extended within an integrated farming system (Little & Edwards 1999, 2003) in which crop and animal wastes or by-products are recycled within fishponds to enhance productivity, and water and mineralized nutrients returned to terrestrial components.

The majority of aquaculture production still originates from earth ponds supplied with fresh water, either rain-fed, supplied by gravity or pumped, while a significant part of coastal aquaculture, particularly for shrimp also derives from ponds, traditionally tidally fed, but increasingly pumped. There has been a gradual trend towards intensification, moving from simple systems, and integrated ponds, towards more targeted, fed systems (Edwards & Demaine 1997; D'Abramo *et al.* 2002). One of the most rapidly growing sectors, however, has been that of cage culture, where stocks are held within suspended net bags in open water bodies such as lakes, reservoirs, rivers, coastal inlets and open sea. High flow-rate intensive systems using tanks, raceways or silos are also used for specialist production. Lower-value species such as molluscs and seaweeds are commonly produced using beds, simple ponds, rafts or suspended or submerged long-lines. Most aquaculture output is marketed at sizes at life-cycle stages similar to those at which equivalent wild stock is harvested. For pelagic species in particular, this is often around the adult/mature stage, typically the point at which the greatest concentrations of wild stock would occur. Distinctions can be made between different life-cycle stages over which aquaculture operates; some control the entire life cycle, others focus on particular stages (Muir 1995). Hatcheries in particular may require specialized skills, with more specific production requirements and can serve demands of a considerably dispersed ongrowing output. They may therefore be more specialized, and more geographically or organizationally distinct. Intermediate stage and grow-out units may deal with biomasses many times those of hatchery stocks and would typically require more significant resource flows. Table 2 outlines the typical features involved for different species groups, with biomass increase at each stage.

Depending on the intensity of production, systems require different levels of resource. While the growth of aquaculture might be welcomed, current trends, based largely on intensification and increased use of external inputs, may not be feasible, with increasing resource constraints. The most common issues are feed and fertilization supply,

Table 1. Total global aquaculture production in tonnes (fish and shellfish only). (Source: developed from FAO (2002*c*).)

country	1995	1996	1997	1998	1999	2000	percentage growth per year
finfish							
Asia	13 484 358	15 306 133	16 858 807	17 829 736	19 318 022	20 482 334	8.7
Europe	881 213	943 287	1 021 647	1 095 411	1 233 821	1 253 934	7.3
South America	216 053	299 476	370 828	396 423	404 725	536 698	20.0
North America	349 119	387 251	440 461	456 286	511 011	519 171	8.3
Africa	95 394	112 792	118 393	176 648	266 005	384 337	32.1
Oceania	15 654	19 151	17 850	21 901	24 726	28 763	12.9
total	15 041 791	17 068 090	18 827 986	19 976 405	21 758 310	23 205 237	9.1
shellfish							
Asia	8 228 922	8 511 281	8 610 777	9 180 924	10 318 376	11 168 554	6.3
Europe	694 153	717 123	712 366	820 132	823 689	768 873	2.1
North America	209 881	179 814	200 493	208 276	222 650	178 748	−3.2
South America	144 238	151 393	186 842	212 424	212 184	155 174	1.5
Oceania	78 583	82 546	87 453	102 214	104 669	100 649	5.1
Africa	4 899	5 280	6 589	6 824	6 933	7 876	10.0
total	9 360 676	9 647 437	9 804 520	10 530 794	11 688 501	12 379 874	5.8

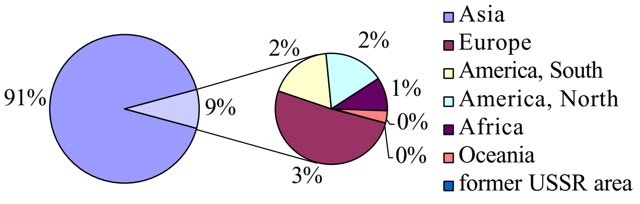

Figure 1. Aquaculture production by continent.

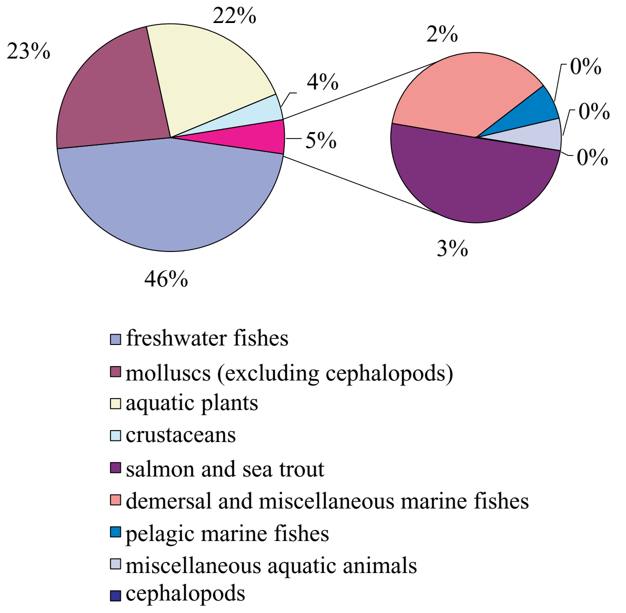

Figure 2. Aquaculture by major product group.

use of land and water, the organic loadings imposed by more intensive aquaculture activities, threats to biodiversity (Beveridge *et al.* 1994; Beardmore *et al.* 1997) and the various opportunity costs of development. To illustrate the scale of waste and nutrient factors alone, open water flows for aquaculture stock, as defined by respiratory oxygen demand, are typically 0.005–0.025 $m^3\ s^{-1}\ t^{-1}$, either conducted through land-based units such as ponds or tanks, or flushed through water-based systems such as cages or longlines. Feed loadings in intensive systems are typically 0.1–5 $kg\ m^{-2}\ d^{-1}$, or 0.01–0.05 $kg\ m^{-3}$ water used, producing waste solids at the level of 0.01–1 $kg\ m^{-2}\ d^{-1}$ or 0.001–0.015 $kg\ m^{-3}$ water used. With water-based units, for example, cage systems, benthic loading below production units, assuming 10–100-fold dispersion rates and average waste outputs, would typically range from 0.0001 to 0.1 $kg\ m^{-2}\ d^{-1}$. On land-based sites, similar amounts would be dispersed into streams, lakes or coastal areas, or may concentrate around the discharge area. Overall, 1000 t of intensive production could require the use (but not consumption) of 100–200 × $10^6\ m^3$ of water, adding 150–300 t of solids, 100–250 t of biochemical oxygen demand, 20–80 t of N, 5–25 t of P, plus smaller quantities of micronutrients, treatment chemicals and other metabolites (Muir & Beveridge 1998).

(a) *Efficiency and productivity*

In strategic resource terms, land and water use, feed ingredient, carbon or nitrogen use efficiency can all be used to define comparative efficiency and potential earning margins. Generic indicators can also be applied, such as total energy input per product output. Of interest as energy costs rise, this also indicates the proportion of non-renewed to renewable energy used, and hence external resource dependence (Stewart 1995). Table 3 illustrates both the wide range of industrial energy efficiency, and the close relationship between intensity and energy supplement. Thus, high-intensity, fed systems, with a high energy input for water transfer and treatment, and a significant stored energy in materials are relatively demanding of energy, and are poorly competitive with many other forms of food production.

For three different systems, table 4 outlines the total embodied energy in production, summing energy incorporated in photosynthetically driven processes (including that used for growing various external inputs) with applied external energy, also demonstrating the marked increase in energy inputs with more intensive systems, and the increased level of resource focusing implied. Though protein output per area is greatly increased in salmonid culture, the input : output ratio is an order of magnitude as high as that for less intensive production systems. Another measure for estimating impact of production—ecological footprint analysis, calculates the additional area required to support the process—both in terms of food supply and in the processing capacity to absorb, metabolize and/or recycle the nutrients involved (Rees & Wackernagel 1994). Here, it has been estimated that for every hectare of intensive salmon production, some 40 000 to 50 000 ha of sea area are required for feed supply and waste processing (Folke & Kautsky 1992, 1996). Though such indices are crude, are difficult to apply accurately and systematically, and have little scope to incorporate resource quality, they illustrate the implications of more intensive production systems, the effects of concentrated fishmeal-dependent systems dispersing nutrients across a wide area, and the nature and extent of possible ecologically based interactions with other sectors. Though current impact assessment techniques are primarily focused on water and environmental quality change, and on local biodiversity impacts, wider assessments are being developed to incorporate technical, economic and social feasibility, together with environmental efficiency (e.g. Kautsky *et al.* 1997; European Commission 2002; FAO 2002*a*, 2003).

At a more practical level, a range of work has assessed actual performance of farming systems, in terms of productivity ranges, factor productivity analyses and marginal returns to specific inputs (e.g. Naegel 1995; Ahmed 2001; Taparhudee 2002; Michielsens *et al.* 2002). This has been valuable both in describing the substantial variability within generic production categories, differences in efficiency, productivity and profitability levels, and the substantial yield gap between idealized or development trial-based systems and actual farm performance. Although a commonly observed feature in agricultural research and development, this has received comparatively little attention within aquaculture until recently.

Unsurprisingly perhaps, the spatial aspects of aquaculture and its development have also received attention, partly from the process of rationalizing site selection and identifying strategic potential, using GIS, and partly for environmental capacity, impact, planning and area allocation purposes (Kapetsky *et al.* 1987; Aquilar-Manjarrez & Nath 1998; Nath *et al.* 2000; Pérez *et al.* 2003). More recently, GIS has been used for linking aquatic production potential with poverty incidence (van Brakel *et al.* 2003) and hence identifying priority areas for development and for examining the implications of major geo-vectors such as climate change. The use of GIS as an exploratory tool to assist in participatory management and resource allocation is also gaining interest, though it remains to be validated in terms of efficiency, decision-making quality, and effectiveness in incorporating social and technical processes.

3. INVESTMENT, TECHNOLOGY CONSTRAINTS AND DEVELOPMENT

(a) *Economic features*

Expected financial or economic returns in aquaculture have been positive enough to generate significant investment at both the public and private sector level. The mix of involvement and the nature of investment vary with the sub-sector, and broadly, coastal fish and shrimp production is dominated by commercial enterprise while freshwater aquaculture, and coastal mollusc and seaweed production has a substantial contribution from smallholder producers (Muir 1995). 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. An important structural characteristic is the degree of aggregation or consolidation, and the extent to which this may change subject to changing conditions of development. One of the basic arguments in this respect concerns the potential for economies of scale to be realized, and hence within a particular sector, for a smaller number of larger producers to emerge.

There is now a growing level of aggregation in the sector as a whole, particularly in more commercial areas, where efficiency gains achieved by larger producers, and their longer-term market relationships are making smaller producers increasingly uncompetitive and vulnerable to takeover (STAQ 1996; Muir *et al.* 1999*a*). Similar trends may also be seen in some of the related and ancillary sectors, such as feed and equipment supply. At the international level, the emergence can be noted of a small number of major 'aqua-industry' enterprises, which are increasingly able to gain strength through coordinated development and marketing, technical excellence and scale-related market (and political) power. Although trends such as these may bring about positive gains in management skill and productive efficiency, there are well recognized dangers in oligopoly power, and concerns in rural economies for local opportunity.

The role of investment is clearly significant, whether as private sector capital or in development funds. Though many agencies understand aquaculture to contribute to development aims, public sector investment has often supported export production and foreign currency earnings—often justified for structural adjustment—or if socially oriented, has been imprecisely targeted to potential beneficiaries and has not always benefited poorer groups. Heavy commercial investment, both local and international, has flowed into more obviously profitable areas of aquaculture; most notably shrimp and marine fish, often at some cost to local resources and environments (Gujja & Finger-Stich 1996; Primavera 1997). As the sector continues to expand, the amounts of investment required for replacement capital, new investment and technology development are significant, though commonly in conditions where a definable benefit in production costs or expanded output, can be proposed. Investment risk has often been considered to be high, requiring evidence of high rates of return, but will tend to be reduced as systems become better understood and develop a longer record of use, as markets become more mature and closely structured and as confidence grows in specific groups, organizations or commercial entities.

(b) *Technology change*

Over the past two decades, aquaculture systems have developed significantly, moving from traditional unmanaged semi-natural methods towards more intensive pond, tank and cage-based techniques. Although such developments

Table 2. Aquaculture production stages and biomass increases. (Source: developed from Muir (1995).)

species	fish	crustacea	molluscs	seaweeds
early	yolk-sac larvae/first-feeding fry; high environmental sensitivity, high-quality feeds; 10–100 × biomass	nauplii, mysis/larvae; rapid change, feed preference, very high sensitivity, very clean environments, good feed; 10–50 × biomass	veliger, unattached, free-swimming/floating; substrates used to collect; may use artificial feed; 5–20 × biomass	vegetative propagules, suspended media, attached, or laid in bed areas; 5–10 × biomass
intermediate or part-grown	fingerling; intermediate sensitivity, feed quality; sometimes change habitat (e.g. salmonids); 5–20 × biomass	post-larvae; medium/high sensitivity, feed quality;may change salinity tolerance, etc; 5–10 × biomass	seed, attached, or laid; beds lanterns or socks; develop and cluster; natural feeds; 10–50 × biomass	transplant stock, may be moved for ongrowing; 2–10 × biomass
ongrowing or growout	market stock; use main production resources; average environments, feeds; 30–100 × biomass	main production resources; average to poor environments, average quality feeds; 50–300 × biomass	main production; beds, rafts, lines; average to good environments, natural feeds; 10–50 × biomass	main production; beds, sometimes rafts; may be continuously cropped; 10–200 × biomass
brood stock	wild, or selected from ongrowing stock; better feed, environments, natural or artificial spawn; 1–10 × biomass	selected or wild stock; better feed, environments; natural or artificial spawn; 1–5 × biomass	selected, indoors, usually feed enriched; environmental stimulus to spawn; 1–2 × biomass	cuttings selected

have not been universally taken up, traditional systems are also evolving, in response to changes in resource availability, economic demand, and to specific technological intervention. A substantial research and development activity has arisen in aquaculture, in both the public and private sector, with a range of scientific and technical outputs. The potential benefits of an effective technology base for the sector are evident, though defining and applying this may be more difficult, and the applicability and effectiveness of various scientific and technical developments might be questioned. Change can broadly be defined as (Muir 1995):

(i) incremental; offering marginal changes over continuing periods, typically over several different areas or production components, commonly by adapting existing systems and processes; the net effect can be significant over longer periods, though instantaneous change may be limited and even difficult to perceive;
(ii) transformational, or paradigm-shifting; where technology offers completely new approaches, offering radically different perspectives for opportunity; often in the process making earlier systems and operations uncompetitive and hence redundant.

The record of development to date suggests that in spite of substantial interest in revolutionizing production technologies, most change has been incremental, though in some cases, small efficiency changes can serve to overcome cost or risk thresholds sufficiently to result in significant acceleration in development. Notable examples of this include both system technologies: better and larger cage systems, improved water treatment and control and biotechnologies: improved feed formulation and manufacture, better stocks, and vaccination against important pathogens. Overall, improved scientific understanding and technical development have meant that systems and processes have become more clearly definable. Increased understanding of functional relationships between input and output and identification of system-mediating processes have combined with technical innovation in monitoring and control technology. Problems such as poor levels of integration between suppliers and reluctance to adopt automation are being overcome and a number of advanced hardware and software products are available to improve management information and system control (Muir 1995; STAQ 2004).

In terms of system technology, the main containment units for fishes and shrimp are ponds, cages, pens, tanks and raceways. Although well established, design and operational parameters are not always well understood, leading to inefficiencies and even failures. Ponds are most suited to semi-intensive production using natural productivity and internal recycling of nutrients. However, this is a complex chemical and biological system, which is not always easy to control or optimize. Cage systems have proved highly cost effective for more intensive culture, but their high degree of environmental exposure results in increased risk of disease transfer, greater problems with predators and less opportunity to control environmental impacts. Tank systems, particularly in combination with water treatment systems, offer the best protection for the stock and for the environment. However, for grow-out,

Table 3. Industrial energy costs for aquaculture. (Source: developed from Muir (1995).)

type of system	GJ t^{-1} of protein	GJ t^{-1} of whole fish
mussels, intensive, long-lines	116	
carp ponds, feeding and fertilizing	250	11
trout ponds, feeding	389	28
catfish, ponds, feeding only	891	25
salmon, intensive, cages	688	56
grouper/sea bass, intensive, cages	1311	95
carp, intensive recycle, feed only	3090	56

particularly if water needs to be pumped, production costs are high. Technical strategies for future development are still therefore somewhat unresolved. Given that the bulk of production and much of the recent sectoral growth has been associated with ponds, a considerable part of future development is likely to be linked with expanded and more intensified pond area. In coastal areas, sheltered sites for marine cage farms are commonly limited, and expansion might require either onshore tank or raceway systems or offshore cage systems able to operate in more exposed conditions. Both have been actively investigated and developed, though inshore cage farming has also developed deeper nets and new feeds and feeding systems that greatly reduce nutrient loadings per unit of production. Hence, the need to move to more expensive technologies has been postponed, although slow adoption is taking place as alternative technologies become relatively cheaper and environmental regulations continue to tighten (STAQ 2004).

Water reuse or recycle systems involving partial or near-complete reuse of process water have been developed for both tank and pond farms (Timmons & Losordo 1994; Blancheton 2000). These help conserve water resources, protect against external risk factors such as disease and pollution, can optimize temperature and other production conditions and can reduce environmental impacts. They usually involve higher construction cost for the circulation and treatment system and higher energy cost in circulating water. Their record to date has been variable, and ongrowing production in particular has been limited by higher production costs. However, particularly in the early rearing stages, they can offer advantages of greater control and flexibility of production. Progress to date on improving reliability and cost effectiveness is mainly due to a greater understanding of system dynamics, increased emphasis on monitoring and control and economies achieved through improved productivity and capacity use.

In coastal areas, the potential for using the large volumes of open water further offshore, with stable water quality and excellent flushing rates, offers good prospects for increasing capacity, with few of the constraints of inner coastal resource use. Recent developments in cage systems, with improved mooring systems, better material selection and better designed assemblies, are making it possible to consider production in genuinely open-water conditions (Muir & Basurco 2000). To date, capital costs are still relatively high, and management procedures still have to be refined, most notably harvesting and associated downstream linkages, but the technical viability is gradually moving towards financial feasibility. This is particularly the case with salmon farming, where company size and volumes of product make it feasible to consider large production units.

4. NEW SPECIES AND GENETIC TECHNOLOGIES

While sound system technologies are essential in underpinning production potential, much of the recent era's scientific and technical interest has been engaged in biological technologies. First, in being able to control life cycles, producing successive generations of stock and second, in improving and optimizing these stocks and their methods of husbandry. The parallel is often drawn with livestock production; whereas in most aquaculture production, stocks are only a small number of generations from wild, livestock production has benefited from selection and genetic improvement over hundreds of years. The potential for productivity gain from aquaculture species may be considerable and evidence to date based on species for which more strategic breeding programmes have developed (Atlantic salmon, *Salmo salar*, rainbow trout *Oncorhynchus mykiss*, common carp *Cyprinus carpio*, channel catfish *Ictalurus punctatus* and tilapia *Sarotherodon* spp.) suggest considerable further scope.

A widely advocated approach for expanding sectoral production beyond current rates is to diversify—normally based on indigenous or established species, though other species could be produced given physical (e.g. land-based systems) or ecological (temperature, salinity or location-separated) barriers. Because of their high value, marine species have been a particular target of research (Utter & Epifanio 2002). Species such as halibut (*Hippoglossus hippoglossus*), cod (*Gadus morhua*), wolf-fish (*Anarichis lupus*), and various flounder species (e.g. *Paralichthys* spp.) in cooler waters and various bream (*Puntazzo puntazzo*), jack (*Seriola* spp.), grouper (*Epinephelus* spp.), dolphin-fish (*Coryphaena hippurus*) Patagonian toothfish (*Dissostichus eleginoides*) and cobia (*Rachycentron canadum*) and other species in warmer waters have been proposed and researched for commercial production. In fresh water, the Arctic char (*Salvelinus alpinus*), hybrid striped bass (*Morone saxatilis*) and the Australian Murray cod (*Maccullochella peelii*) have also attracted recent attention, for similar reasons and because of apparent tolerance to highly intensive rearing conditions. However, these often occupy similar market niches to those species already produced, further congesting markets. The time and cost needed to bring new species into production may be difficult to recoup through the gains of a 'honeymoon period' (Young & Muir 1995). Though these may reduce, as knowledge and skills can be transferred and as generalized understanding emerges in genetics, reproductive, behavioural and energetic physiology, feed formulation and system design and operation, significant time may still be required to develop a distinctive and sustainable production sector. The structural features of commercial and institutional agents have also been significant in determining the rate of progress and the success in developing new species will include issues of biotechnical development, marketing responses, industry structure, support frameworks and cost benefit features at enterprise and sectoral levels (Muir & Young 1998, 1999).

Table 4. Total embodied energy relationships, for equivalent area.
(Source: developed from Muir (1995).)

quantity	seaweed culture	mussel culture	cage salmonid culture
energy inputs	(kcal × 10^5)	(kcal × 10^5)	(kcal × 10^5)
solar/renewable (%)	0.30 (4.5%)	0.75–2.05 (71.4–85.4%)	470–830 (81.0–87.4%)
fossil/non-renewable (%)	6.35 (95.5%)	0.30–0.35 (28.6–14.6%)	110–120 (19.0–12.6%)
total energy	6.65	1.05–2.40	580–950
protein output	6605 (kcal)	255–440 (kcal)	22 420 (kcal)
input/output ratio	100	410–545	2585–4235

(a) *Seed stock*

The availability of good-quality seed stock is still a constraint to the development of aquaculture (Edwards 2001; Mair 2002). Better management of reproduction not only ensures an adequate supply of seed, but also offers the potential for genetic improvement of stocks or the manipulation of gender. The basic quality of embryonic and early life-cycle stages of aquaculture organisms, and the husbandry and biological conditions have a crucial impact on subsequent performance in terms of growth, fitness and reproductive capacity. There are three critical parameters; (i) the fitness of brood stock, and the mechanisms by which biochemical and other quality features are transferred; (ii) early rearing nutrition; and (iii) the early rearing physiological environment.

For salmonids, the main concerns now relate to all-year-round provision of stock. For salmon, and most other cultured species, there is also a need to inhibit maturation or control gender to avoid maturation in pre-market sized fish as physiological changes associated with maturation can adversely affect growth performance and marketability. For many marine fish and shellfish species, which commonly produce very large numbers of very small seed, major concerns relate to the husbandry and management of brood stock and the effects of these parameters on the quality of eggs, post-larvae, or yolk-sac and first-feeding fry (STAQ 2004). First-feeding stages are commonly dependent on live feeds, artemia and rotifers, whose nutritional composition is difficult to control, resulting in highly variable survival, quality and performance. Rainbow trout producers increasingly select all-female stocks for better growth rate and less risk of precocious maturity, while tilapia on-growers prefer all-male stocks as they grow faster and as with mixed-sex stocks, precocious breeding results in increased recruitment and competition for resources in ponds, and hence reduced production. There are similar issues for other species (Penman *et al.* 1995), though with some exceptions (e.g. carp) background information and appropriate strategies are not always as well understood.

(b) *Breeding programmes and genetic manipulation*

The traditional approach to stock breeding has relied on basic techniques of stock selection, often based on simple parameters such as size, in many cases with very little consideration for attributes such as fitness, disease resistance or tolerance to specific conditions (Penman *et al.* 1995). More importantly, many local programmes, based on limited stock numbers, very quickly reduced heterozygosity through inbreeding. Other management practices have resulted in negative selection and contamination by feral stocks, all of which result in inferior stocks. Recently, the need to work with very large founder stocks has been reduced using DNA microsatellites and other genetic markers. It has become feasible to identify multiple selection goals, and devise practical strategies for stock improvement. Active improvement programmes now exist for salmon, Mediterranean sea bass and sea bream, tilapia and several species of shrimp. Improvements in growth rates of over 10% have been achieved, and in the case of shrimp, improved resistance to specific viral diseases has also been claimed (STAQ 2004).

One of the most active areas of current research has been in developing simple forms of genetic manipulation. Aquatic organisms are particularly susceptible to genetic and ploidy manipulation (triploidy, gynogenesis and androgenesis[4]) (Hulata 2001). Single-sex populations of rainbow trout, Atlantic salmon, brown trout and a wide range of tropical species are now commonly used, and manipulation of gender and sexual maturation are likely to be important for many other new species. Using a combination of hormone sex reversal and ploidy manipulation it is possible to rapidly produce new strains that will directly produce single-sex offspring hence increasing production potential. Such techniques can also avoid potential consumer concerns over the direct application of hormones, albeit at minute and subsequently undetectable levels, to produce single-sex fry.

At a higher level of technical sophistication, the use of transgenic techniques, and the potential for increased growth, environmental tolerance or disease resistance, could result in significant change (Dunham 1999; Maclean *et al.* 2002; Maclean 2003; Maclean *et al.* 2003). Transgenic animals contain genes and promoter sequences that have been injected into the developing egg and become incorporated into the genome of that individual. Dramatic increases in growth performance (*ca.* 600%) have been reported, particularly in salmon. However, transgenesis is perhaps the most contentious area of current scientific engagement for the sector, because of the ethical and environmental implications as well as public perception of the new strains being developed (Anon. 1998). Though a number of government, university and industrial groups are currently exploring this area, any timetable for commercial exploitation is still uncertain. A possibly less contentious route may be that of autotransgenesis, whereby only genetic material from the same species is used, thereby avoiding the concerns about use of ‘foreign genes’. Although some initial progress is being made with tilapia (N. Maclean, personal communication) technical effectiveness and consumer and policy responses are yet to be determined. Regardless of approaches and outcomes, and assuming remaining technical problems are overcome and consumers accept the products, the biological containment (or sterilization—possibly using reversible sterility) of transgenic strains will be essential to avoid any risk of contamination of the wild gene pool.

5. PRODUCTIVE INPUTS: FERTILIZERS, FEEDS AND NUTRITION

At simple levels, in directly photosynthetically driven systems such as fertilized ponds, the aim is to stimulate productivity, harnessing normal ecosystem and nutrient transfer processes in favour of the production of desired species (Pant *et al.* 2001). In much of current aquaculture production, yields are much lower than those attainable in well fertilized and well managed systems, in which species and biomass of production is adjusted effectively to make best use of feeding niches. More nutrient-dense eutrophic systems also tend to be more unstable ecologically, requiring greater management skill and better provision for risk management. Of increasing recent concern is the potential for bioaccumulation or bioconcentration in food chains and the extent to which food safety may be compromised. While considerable research continues in optimizing nutrient input, exchanging benthic and water column nutrients and selecting species mixes with good potential for feeding efficiency and productivity (e.g. Avnimelech *et al.* 1986; Diana 1997), practical constraints of nutrient availability, climatic variability, seed supply, management knowledge and market acceptability are very significant in many sectors of aquaculture production. However, the potential for increasing yields in much of the existing extensive and semi-intensive sectors is considerable, and evidence of such change, and the means to promote it, is increasingly available (Colavito & Chowdhury 2002; de Graaf & Latif 2002).

(**a**) ***Integrated aquaculture***

A continuing focus of interest for intensifying production in rural and peri-urban areas lies in integrating aquaculture. In water use, nutrient transfer, labour and management input, aquaculture is combined with other activities, most commonly domestic, agricultural or agro-industrial, to improve the use of otherwise underused or sometimes potentially damaging waste materials. Integration is used to improve nutrient cycling and overall ecological efficiency in delivering harvestable and/or marketable product and, most crucially, in many contexts to widen employment, income and livelihood opportunities in poorer households (Little & Muir 1987; Zhang 1990; Little & Edwards 2003). A further interest has remained in the potential for aquaculture within waste treatment systems as part of small urban or even large city sanitation systems, either as a specifically designed and managed approach, or more informally, using nutrients available in stabilization and maturation ponds (Edwards 2000*a*). The theoretical potential for production and food supply and for making sanitation investment more viable in many developing countries is immense, but institutional constraints associated with management, peri-urban land use, markets and investment agency support, are widespread (Morrice *et al.* 1998; Mancy *et al.* 2000; Little *et al.* 2002).

Different forms and approaches to integration can be recognized and it is not practical to generalize with respect to effectiveness or practicality, as issues such as labour demands, skills, transport/value relationships and potential disease or zoonosis transmission may all be relevant. In general, however, diversifying crops, simultaneously or sequentially can yield valuable benefits and relatively simple practices can be taken up quite widely. At a more challenging level, integrating intensive with extensive aquaculture or waste treatment systems has also received increasing interest, ideally in reducing the production footprint and creating a ‘zero-discharge’ production (Bunting 2001). However, these have yet to demonstrate their effectiveness (Brix 1999).

(**b**) ***Feeding intensive aquaculture***

Intensive aquaculture has a high reliance on relatively high-protein feeds. Marine fishes also appear to require high levels of mainly marine lipids. Fishmeals have long been the protein source of choice, for reasons including their protein concentration, quality (essential amino acid balance and digestibility), palatability, freedom from toxic and/or anti-nutritional factors (a common problem with feedstuffs of plant origin) and their competitive cost per unit of protein (Hardy & Tacon 2002). These materials are generally derived from shoaling marine pelagic species such as anchovy and sand eels, with the majority of world production originating in South America. World production remains fairly constant (6–7 mt yr^{-1}) in the face of rapidly increasing use in aquaculture, particularly for salmon, sea bass and sea bream, and shrimp.

In biomass and ecological terms, the use of fishmeals in aquatic feeds is inefficient; thus Tacon & Barg (1998) estimated that in 1995, global production of farmed carnivorous fishes and crustacea, just over 3 mt, were fed with 1.5 mt of fishmeal, equivalent to some 5 mt of small pelagic fishes. This contrasts with tropical semi-intensive fish production where little or no fishmeal is used and terrestrial animal systems that are net animal protein producers. It has been estimated that aquaculture now uses some 20% of current world fishmeal production. It has also moved towards using higher grades of meal, made from the freshest fish and processed at low temperatures, as these offer improved protein digestibility and palatability, leading to faster growth and lower FCRs (kilograms of food required per kilogram produced) (Pike & Barlow 2003). By controlling feed composition, it is also possible to change product composition. The commonest modification is that of adding pigments, although there is potential for other alterations to appearance or nutritional content.

Most cultivated fishes, especially carnivores, have an essential requirement for n-3 fatty acids, whereas terrestrial animals require n-6 series fatty acids. High levels of these can only be effectively obtained from marine fish oils, although genetically engineered plant materials may offer a partial solution in the future. These oils are not only good sources of n-3 fatty acids but are also highly palatable, highly digestible and result in farmed fishes having similar n-6 : n-3 carcass ratios to equivalent wild fishes. However, rising consumer health awareness has also increased competition for fish oils from other users such as new ‘high n-3’ margarines or as encapsulated human health food products. More recently, however, increased concerns have arisen for the potential contamination of marine food chains, particularly with fat-soluble molecules, of which dioxins and PCBs are particularly noted (FSA Ireland 2002; Jacobs *et al.* 2002; Lindstrom *et al.* 2002). In addition to pushing the health-food supplement industry to ensure product quality, improved and more sensitive analytical techniques are also highlighting potential concerns for further accumulation when fed to aquaculture stocks. These issues have in turn posed even greater challenges and competition in sourcing oils with the lowest possible levels of contamination (Pike 2002).

Highlighted in part by ecological critiques of the development of modern intensive aquaculture (Naylor *et al.* 1998, 2000) there is also increased pressure from conservation groups and consumer interests to limit industrial fishing for meal and oil. While the aquaculture sector competes on global markets with other livestock producers, its marginal value per unit of fishmeal, or more critically fish oil, has tended to be greater and it has remained a highly competitive purchaser and a view can be proposed that this will ensure acceptable levels of future access to raw materials (Barlow & Pike 1997). While technical alternatives are starting to emerge and are becoming more viable (Bell *et al.* 2003) and a shift towards less carnivorous species, or stocks which are genetically less dependent on these nutritional inputs, may reduce demands for these raw materials, the supply of fish oil and fishmeal is likely to be critical in shaping the sector's future development.

(c) *Feeding methods and technologies*

Most intensive aquaculture is now based on dry, compound, feeds. These are convenient to handle, have a relatively long shelf life and are of consistent quality. Over the past decade, improved feeds have provided better feed-conversion ratios and reduced waste and extruded pellets and the over-oiling of feeds have provided further benefits. The current generation of expanded diets is less dense and more robust, sinking more slowly, allowing the stock more opportunity to eat and producing less waste. A further advantage is that high pressure feed delivery systems can be used to disperse food to the fishes over a large area without the food breaking up. Non-expanded pellets tend to disintegrate in such systems producing fine particulates, which are not eaten but adversely affect water quality, damage gills and reduce FCRs. Other advances have been in the introduction of feed attractants and stimulants in the feeds, new pigmentation enhancers and more stable forms of vitamins (STAQ 2004).

Most species respond positively to being fed small amounts of food frequently, which with traditional hand-feeding, is laborious and expensive, though many producers still do so, to observe stocks during feeding and adjust rations according to their reaction. Regardless of the feeding strategy, with increasing size of production units, a range of systems is used to distribute feed. Automatic feeders, feed blowers or water/air cannons operated from boats are commonly used in large cages and tractor mounted blowers in large ponds. The reaction of stock to feed is one of the few means to judge health and environment; even with sophisticated systems, it may be necessary to use observation to adjust feeding rates and rations. However, computerized feeding systems that can adjust feed quantities depending on temperature, season and time of day are increasingly common in the intensive aquaculture sector. A further refinement is to use sonic or video monitors to judge stock movement and behaviour, or to monitor levels of uneaten food, and thereby control feeding rates even more accurately.

6. ECOLOGICAL INTERACTIONS

The primary set of ecological interactions in most aquaculture systems comprises those that drive energy and nutrients towards targeted production. These are commonly the concern in management and relate to the fertilizing and feeding strategies just outlined, together with the metabolic output and recycling features noted earlier. However, a range of other, often less tractable interactions can be described, at times creating significant constraints. In a general perspective, these tend to be more important in more energy and nutrient-dense (i.e. more intensive) systems, but this is not always so.

(a) *Aquatic health management*

Fish and shellfish disease is widely accepted as one of the most serious threats to the commercial success of aquaculture. Stock losses of more than 20–30% can occur in serious disease outbreaks and for especially sensitive stocks or life-cycle stages, almost complete mortality can result if disease is untreated. If stocks survive, they may be damaged physiologically or reduced in market quality, both of which represent serious financial loss. Disease treatment varies considerably with species, disease status and husbandry conditions, ranging from simple measures to improve water quality and reduce stress, cleaning out sources of contamination and disease transfer, application of drugs and other chemicals, orally, by immersion or by injection, with specific or general control of pathogens and increasingly, vaccination (Ghittino *et al.* 2003). Finally, complete eradication and sterilization may be required for particularly dangerous pathogens. There continue to be significant problems in many areas, with little respite from continued vigilance, research to identify pathogens and their strains, appropriate and effective methods of treatment, and longer-term approaches to maintaining stock and industry health status.

Although there have been many useful advances in disease diagnosis and treatment, the greatest impact has probably been through immunology, with techniques applied in two major areas of aquatic disease control—diagnosis and vaccine development. The development of antibody probes to pathogens provides useful tools for rapid diagnosis using techniques such as immunohistochemistry, immunofluorescence and enzyme-linked immunosorbent assay. Initial prevention from infection is the optimal strategy for disease control and vaccination has proved highly effective in improving survival rates for salmon, with a very significant reduction in antibiotic usage. Fish vaccines have become much more sophisticated, with a trend for the development of subunit recombinant vaccines, in preference to killed whole cell preparations, as the latter did not succeed for many important diseases and attempts to produce attenuated vaccines in general have encountered safety concerns. The most recent development is direct DNA vaccination, which appears to offer efficacy and low cost and is being developed commercially for infectious salmonid anaemia virus in salmon. Another molecular genetic technique is the polymerase chain reaction method of DNA amplification. This is increasingly used to detect the presence of pathogens (e.g. specific viruses, bacteria and parasites) in the culture species or environment before the appearance of clinical disease, greatly improving the prospects for managing the problem before an outbreak occurs (Villena 2003).

In the less intensive and lower-value aquaculture sectors, disease management has proved to be much more difficult to put in place and apart from routine disinfection and preventative treatments for hatchery stock and limited attempts to control and possibly quarantine introduced stocks, has generally had much less impact. This has been a significant challenge, as the majority of production risk and productivity loss would appear to be associated with non-existent or poor health management (MacRae 1998) and there have been a number of epidemic conditions such as white spot virus in marine shrimps and epizootic ulcerative syndrome in freshwater fishes which have caused substantial losses, driven out significant numbers of producers and for which it has been impossible to provide effective management responses. Recent work on developing epidemiological techniques (Corsin *et al.* 2002) has however shown potential and this is now being extended to explore how these may be used to change institutional processes from the traditional focus on pathogen diagnosis, with very limited effective feedback, to more solution- and outcome-driven approaches.

A further area of concern relates to food safety as related to aquatic and ecosystem health (Howgate *et al.* 2002), with increasing potential for contamination and bioconcentration in many peri-urban and rural areas, particularly in developing countries (Sadhukhan *et al.* 1996; Reilly & Kaferstein 1997). This may be accentuated by a relative lack of awareness of risk, limited analytical capacity, poor policy response and generic under-investment in sanitation. The increasing interest in developing aquaculture for export and foreign exchange earnings, will however lead to greater sensitivity, with considerable commercial risk being attached to rejection of product or market closures. This may increasingly become an issue of competition in global markets, with local lobbying to restrict imports because of suspicions about safety (Young & Muir 2002*a*).

(b) *Predation*

Predators and scavengers cause direct and indirect impacts, including killing or wounding cultured stocks, increased stress and disease transfer. Predators include species such as squid, fish turtles, lizards, sea snakes, and birds and mammals associated with the aquatic environment. These are commonly present owing to the ready supply of food, or in cage culture, to wild populations of fish attracted by uneaten food. Cages and ponds may also serve as a roost or observation site for opportunistic scavengers. Although reliable figures on economic impacts are scarce, predator related losses estimated in 1987 for the Scottish salmon industry were £1.4–1.8 million, and in British Columbia estimated at $10 million for 1996 (STAQ 1996). In inland areas, losses owing to cormorants, herons and other predating birds are also considered substantial, while frogs can have a serious impact on fry and fingerling stocks.

The main approaches to predator management (minimizing economic impact) are exclusion (netting and other physical barriers), harassment (acoustic deterrence, scaring devices and guarding) or if necessary, removal (shooting, trapping). Most farms deploy perimeter fences to protect against terrestrial predators and use strings, wires or netting over water areas to protect against birds. For floating or immersed systems, for example, to protect mussels from eider ducks, or fishes from diving birds and sea mammals, underwater netting (on sides and occasionally bases) may be necessary. Effective if correctly sized and installed, they can be destructive if predators are caught. Scaring devices (usually ADDs) can be used against dolphins, seals, otters and birds. Acoustic pulses are propagated outwards from the farm units, usually from multiple transducers with overlapping fields, strongly enough to cause discomfort to any approaching marine mammal. The ADDs usually provide up to 3000 m^2 of protection. More complex 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. ADDs are reportedly effective for up to two years, though diminishing with time, especially for seals, which learn that pulses can be withstood. Long-term impacts are not conclusively known, but they may interfere with communication and with passive listening abilities. They have been linked to declines of baleen and killer whales, leading to a ban on their use in British Columbia, Canada. ADDs for birds mostly involve sudden loud noises, with similar problems of habituation and greater issues of sound pollution. Laser rifles are also available which scare rather than kill or wound (STAQ 2004).

(c) *Introduced species and stock escapes*

The introduction of species or strains into productive habitats for aquaculture, for stock enhancement, or for culture-based fisheries can have significant implications for biodiversity (Beveridge *et al.* 1994; Leach 1994; Myrick 2002). If stocks are to be released in open waters, the need for careful appraisal is very clear, though this has been surprisingly absent in many interventions globally and is only now becoming a specific management issue. For most forms of aquaculture, where stock are intended to be contained for ownership and management purposes, a key priority is to prevent stock escape. However, especially with immersed and flow-through pond or tank systems, complete containment is difficult, with losses of small numbers of stock during routine operations such as stocking, grading and disease treatment and very occasional mass releases due to storms, predator damage and accidents (Skaala 1995). Information on the incidence and quantity of escapes is limited, as statutory requirement to report these are currently uncommon, though Beveridge (1996) estimated escapes of up to 1.5% of fish stocked in cages. Performance is reportedly improving as trade associations attempt to introduce new codes of conduct and a target of zero escapes. Nevertheless, a reported 411 433 salmon escaped from Scottish farms in 2000, while 613 000 salmon and trout are through to have escaped Norwegian farms in 2002 and around 900 000 (4500 t) in Chile (STAQ 2004).

Three main interactions can be identified; abiotic (habitat damage), biotic (increased competition and predation) interactions and genetic introgression between farmed and wild stocks. The first is rare, though an example is grass carp introduced to the eastern Mediterranean, which feed voraciously on plant material and affect biodiversity and wildlife habitat. However, they do not breed there, thus limiting impacts. However, introduction of the red-clawed crayfish in areas of Portugal and Spain has caused considerable damage to irrigation ditches and loss of rice production (Beveridge 1996). The risks may be greater if stocks are exotic. Although some 200 aquatic species are currently farmed, only a small number contribute to the bulk of output and have been widely translocated, inevitably escaping into local environments. Shellfish farms may also be a source of interaction and for example, all introductions to the Mediterranean may now be found in the wild. The escape of salmon is especially sensitive and can occur at all life-cycle stages, potentially surviving to breed with local populations. The fitness of escaped stock for survival in the wild is often much lower than equivalent naturally raised animals, hatchery environments resulting in lower levels of physical fitness and changes in behaviour related to feeding and territoriality. These relate to the time the animals spend in the hatchery or farm environment and may result in lower reproductive fitness because of behaviour deficiencies at spawning (Youngson *et al.* 2001).

This suggests that few escaped fishes will breed successfully, but if numbers are high, they may swamp the native stock and lead to genetic dilution (Youngson *et al.* 2001). Between 20% and 40% of the salmon caught in the Faroese fishery and 50% in Norway, are of farmed origin (Hansen *et al.* 1999). While this may, in some circumstances, lead to reduced fitness and productivity, widely reported declines in wild stocks are associated with a complex interaction of factors, including overfishing, habitat destruction and climate change. The effects of escaped stock on the native gene pool are difficult to assess, as they may sometimes also help to increase or maintain genetic diversity if this is declining. However, if reproductively isolated salmonid populations are naturally adapted to a given environment, the introduction of new genes may reduce the long-term fitness. However, studies on farmed fishes show that environment and feeding success can change the relative proportion of different life strategies in farm populations. In salmon, a single genotype 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). This is probably less problematic for marine species such as cod, haddock and halibut, which generally have much larger population sizes and ranges.

In very different circumstances, the development of carp aquaculture in South and East Asia, and that of tilapia production in Asia, Africa and South America, may also be associated with reduced genetic diversity. In the first case, production may develop alongside a reduction in wild fisheries owing to overfishing, regulation of surface waters and/or reduction of spawning habitat and be accompanied by widespread distribution of hatchery stocks deriving from a relatively narrow genetic base. Current evidence suggests that many of the carp stocks in Bangladesh, for example, have greatly reduced levels of genetic diversity and that a strategy for avoiding introgression will be urgently required (Penman *et al.* 2002). For tilapia, the primary concerns relate both to the group's highly successful adaptability to non-native habitats and the relatively narrow base from which aquaculture stocks are derived, particularly with artisanal fry production from which inbreeding and selection of early-maturing small fishes commonly result (Beveridge & MacAndrew 2000).

It is likely to be more common, particularly where habitats and stocks are more comprehensively protected, to compare different natural populations for commercial potential, identify the genetic differentiation involved and to develop both production and biodiversity strategies. Island environments with significant migratory distances to other inland or coastal habitats and less critical local conservation concerns may also adopt a more open strategy to stock introductions, though this too would require careful evaluation. As stock escapes are also highly undesirable for the producer, the technical improvement of containment systems and improved management and maintenance are probable strategies and may increasingly be enforced by regulators. In some cases, sterilization as a form of genetic containment may be another option, though this may not fully protect against local habitat damage.

7. SOCIAL AND ECONOMIC ISSUES

A wide range of social and economic issues can be identified in the perspective of aquaculture, its development and interactions and these in turn link closely with policy and institutional features. Useful parallels may be drawn with other sectors, particularly agriculture and food supply (Goss & Burch 2001), and within the wider contexts of rural economies, urbanization, economic growth, trade and income distribution. Two particular themes are outlined here, first the involvement of people in production and services, and second the characteristics of demand.

(a) *Employment and social policy*

It is common for many central and local government agencies to develop and promote policies for employment and economic development, within which aquaculture can prove an attractive technical option, especially in economically fragile rural areas and those with contracting capture fisheries, thus including upstream and induced income expenditure multiplier effects. Salmon farming in Scotland is estimated to support approximately one job per 20 t of production (approximately 6500 jobs in 2003), each generating *ca.* £43 000 per year for the Scottish economy. As in other sectors however, productivity gains are reducing such impacts, rising from *ca.* 15 t per person per annum in the late 1980s to 110 t by 2001. Productivity is higher in Norway (132 t per person in 2000), only just below that for capture fisheries (135 t per person). The number of people employed in coastal fish culture has fallen in Norway by 50% since 1988, while in Scotland it has declined by over 6% since 1990 (the highest employment point), while production continued to rise. Downstream employment in processing and distribution is more significant, estimated at 1.7 times production employment in 1996 (PACEC/STAQ 1999), though here too, economies of scale and mechanization are likely to involve increased labour productivity over time.

Table 5. Approaches to adoption and development of aquaculture. (Source: developed from Muir (1995).)

subject	associated issues	implications
entering the sector	expectations, external incentives, credit/investment, ownership, family and community circumstances, trust in promoter	fundamental determinant of scale and nature of aquaculture production from new entrants
choosing species and system	background beliefs or knowledge, familiarity with species or systems; attitudes of peers, wish to compete/be more progressive	defining the type of system employed, resources used, type and value of output
increasing productivity	desire for profit, attitude to risk/allocation of more resources, ability to control system; desire to be progressive	level of management input, resource needs, economic activity, output levels and overall efficiency
using new stocks	background beliefs; attitude of peers, extent of dependency; desire to appear progressive	extent to which improved strains can be introduced
using new species	views of local markets, background beliefs or knowledge, familiarity with species	possibility of diversification, developing polycultures, new markets
changing production plans	extent of confidence that changed practice can result in changed outputs and better returns or less effort	prospects for improving efficiency, productivity, resource use, output, changing employment
environmental management	understanding of the issues, and concept that there may be local effects	overall resource quality, sustainability, potential for expansion without environmental degradation
developing new markets	confidence in existing operations, attitude to risk, ability to communicate outside local context and/or establish trading links	widening opportunities, better economic returns, food supply benefits
expanding production	attitude to risk/allocation of more resources, ability to control system; desire to appear progressive	basic determinant of extent to which production can grow from existing participants; wider benefits; resource demands; economic returns

Future patterns of employment in the intensive sector depend on technologies employed and its level of expansion. Further improvements in productivity appear likely, although job numbers could be increased through diversification both in production and processed products. However, the quality and mix of jobs and the contribution they make to social cohesion and welfare must also be considered. The same review (PACEC/STAQ 1999) found 85% of employees in production to be male and predominantly manual (13% skilled, 49% semi-skilled and 19% unskilled). The remaining 18% of male employees were non-manual, mainly managers, sales staff and professionals. Approximately 61% of female staff were manual (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 *ca.* 59% of employees being male, and 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, but the net gain in more skilled employment is likely to be slight.

By contrast, employment in other aquaculture sectors, particularly where smaller-scale activities continue, such as in oyster and mussel farming, and in lagoon culture and fisheries of mullet, sea bass and sea bream in the Mediterranean, employment levels, though sometimes seasonal and part-time, are generally higher, and represent a greater part of input cost in the production system. This is sometimes also enhanced by significant secondary employment in the supply and market chain, though still seasonal and part-time. However, in production and value terms, these sectors are becoming less important, and occupy a far smaller part of the wider sector, with most of the future growth and expansion being associated with larger and more intensive production systems.

A critical aspect of development, particularly where there has been little growth or uptake in the past, is the adoption of aquaculture as an activity, or of improvements to make it more viable and effective. In the earlier stages of aquaculture development, it was recognized that extension would have an important role, but widely assumed that openly demonstrated benefits of aquaculture would require little additional incentive for expansion. However, as implied earlier, this view had proved over-optimistic, and as already occurring within the agricultural sector, had prompted closer analysis of the processes of adoption (Harrison 1994, 1997; Harrison *et al.* 1994). Some of the key aspects of the process of adoption itself are summarized in table 5, which is subdivided into critical areas of decision and development, and identifies the types of issue that may contribute to the decision or response to a proposal for change.

In developing countries, the widespread involvement in smallholder aquaculture and the diversification of employment and income associated with the sector is considered very important in social and economic development where practical opportunities exist (Edwards 2000*b*; de Graaf & Latif 2002). However, as in more developed economies, there are also concerns for commercialization, and the growing dominance by larger-scale producers, or richer entrepreneurs acquiring local productive assets. Thus in Bangladesh, it is estimated that freshwater fish culture had grown by some 20% per annum over the last decade, with production of *ca.* 750 000 t in 2000, involving more than 300 000 ha of freshwater ponds and more than 900 000 households. In addition, in 2000, some 37 400 shrimp ponds

Table 6. Sustainability indicators for aquaculture.
(Source: developed from Stewart (1995).)

system	indicator class	examples	direction of change for increasing sustainability
economic	financial	profitability, value addition, investment recovery, risk management	increasing
	economic	employment—direct/indirect exports, values, structural stability, fiscal returns	increasing
environment	impacts known	water quality (nutrients, oxygen)	reducing /minimizing impact improving quality and diversity
		land use change, loss or change of habitat and biodiversity	
	impacts uncertain	use of chemicals and drugs: (potential for bioaccumulation /resistance: ecosystem and human health implications)	reduction in use, control of potential impact, mitigation measures
		species and genetic variant introductions, disease introductions	reduced levels of introductions and movement, better containment
	resource use	non-renewable (fossil fuels: related to level of intensity, and source of feed)	increased efficiency; decreasing dependence
		renewable (related to level of intensity, trophic level of species, source of feed)	increased efficiency; decreasing resource imports; increasing integration
social	welfare	nutritional/income benefits (increasing consumption by/earnings of those in need)	decreasing cost of fish/accessible to those in need
		community stability (viability of schools, shops, rural economy in general)	activity accessible to those in need; increasing diversity of activity
		product safety/ quality; health and safety at work	decreased use of chemicals and drugs
	equity	change in wealth distribution, and access to and control of resources	decreased equity gap; subsistence activities valued in economic assessment
	rights	level of participation in decision-making	increasing participation in local development and resource management

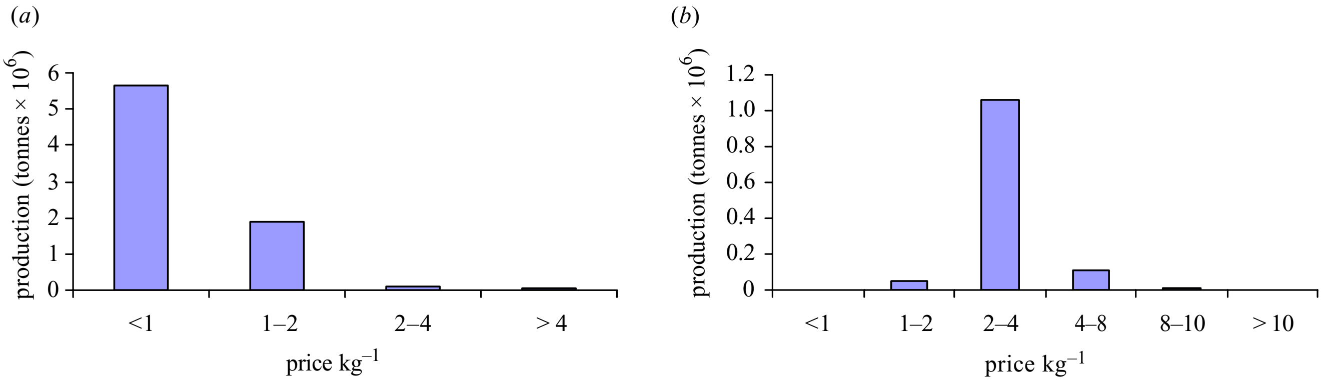

Figure 3. Volume–price relationship for (*a*) capture fisheries and (*b*) aquaculture in Europe. Source: STAQ (2004).

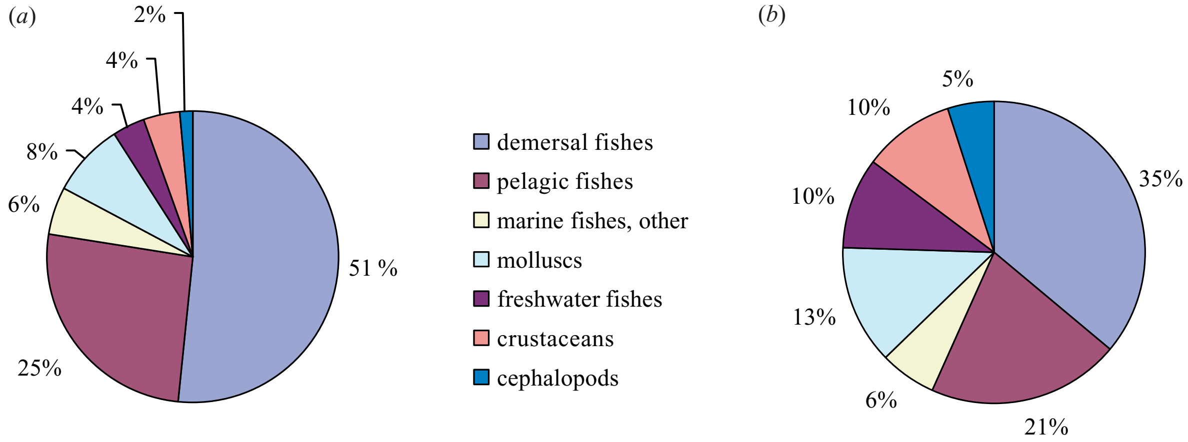

Figure 4. Patterns of consumption change in EEA for (*a*) 1970 and (*b*) 2000.

extending to 170 000 ha produced 33 000 t of shrimp, together with 37 000 t of finfish and 1800 t of mud crab (FSRFD 2003). However, while smallholder producers were still an important part of this (Begum & D'Costa 2002), the advantages possessed by wealthier families and the difficulties of targeting involvement amongst the poorest social groups, were widely noted. Though a widely quoted exception however was that of small-scale cage culture, typically involving landless women producing many kilograms of fish annually in units of 1 or 2 m^3, many risks were identified for their future opportunities. The role of more commercial, export-oriented aquaculture in providing employment is also an issue, and while considerable opportunities may be identified, including those for women (Hamid & Alauddin 1998; Ahmed 2001) there are equal concerns for the quality of this employment, and vulnerability to global trading conditions.

(b) *Consumer demand*

Many perspectives on aquaculture development have focused on production technologies and their potential, and have highlighted science and technology. While these have been important drivers for growth, the development of markets and research into consumer understanding and preference in the rapidly changing environment of food markets, have been equally if not more important. It is now almost a truism that aquaculture development is market-driven, but this may still be less obvious than in other sectors. Within international food markets capture fisheries are unique, as the last major sector to rely on a hunted supply base. However, this supply increasingly interacts with aquaculture production. The potentially destructible basis of capture stocks, and the rapid expansion of investment in aquaculture, coupled with high product perishability and changing consumer preferences, have combined to make the fish marketing environment increasingly dynamic and vulnerable. Traditionally, the variability of capture fisheries, product life and distribution features had created relatively complex market chains, linking small fishing units to local retailers and consumers across large areas. However, the development of aquaculture, with increased reliability of supply and quality, flexibility of product form and availability and larger production units, together with the increased presence of multiple retailers with greater buying power, has tended to shorten and simplify market chains and reduce the potential for adding value within these. In developing countries also, increased urbanization and improved transport links are also serving to stimulate domestic markets, increase product flow to commercial outlets, and reduce food supply access for poorer rural communities.

An important issue related to aquaculture is the extent to which it meets environmental and social aspirations of intending consumers, particularly in the more prosperous markets to which much of the more intensive sector is focused. Though such attributes have been much less emphasized with capture fishery products, there is an increasing concern that aquatic products are properly sourced (Best 2002). Concerns for the use of chemical treatments and pharmaceuticals and on the accumulation

Table 7. Scenarios for future development.
(Source: developed from STAQ (1996).)

species diversity; low genetic-linked gain	species diversity; high genetic-linked gain
wide range of species primarily occupying high-value markets, some being forced to operate at very low margins; increasing competition from imports, but moderate opportunity for replacing appreciated capture fishery stocks with 'natural' products. Possible opportunities for small-scale producers; low to moderate growth potential, potentially good conservationist image associated with unmodified stocks, though careless strain management could be negative	wide range of species, but limited degree of product development; flexible opportunity to occupy high value markets or compete with lower cost, for example, capture fisheries and other food product markets. Moderate to high growth, but constrained by acceptance of product form. Biotechnology skills/costs may favour larger producers, but licensing may allow small-scale producers to participate. Neutral-poor conservationist image may be improved with biodiversity support programmes
product diversity; low genetic-linked gain	product diversity; high genetic-linked gain
limited degree of further development of other species—only to the point of niche markets, and developing high-quality specialized profiles for producers; otherwise widening product base for 2–3 main species, with steadily levelling prices. Moderate growth, with dominance by primary species, and steadily increasing penetration of traditional markets, possibly disadvantaging traditional suppliers	some degree of development of other species, but substantial development of product forms based on steadily reduced prices of key species. Potentially very high growth, major food supply consequences, and primary role of large-scale producers and specialist biotechnology suppliers. Very limited opportunity for specialist and small-scale producers, reduced pressure on wild fisheries owing to low prices may improve conservation impact, reducing fishery employment

Table 8. New areas of aquaculture potential.
(Source: developed from Muir (1995).)

area of development	products, characteristics	potential
water treatment and habitat restoration/improvement	stocked aquatic organisms—constructed wetlands, phytoplankton grazers in lakes and reservoirs, nutrient cropping in waste treatment lagoons, macrophyte consumers in streams, irrigation systems	wide potential and proven impacts, though concerns for food safety in more contaminated systems may require controls on harvest/consumption or use as secondary feeds
nutritional enhancement	'high-health' protein or lipid modified products of conventional format, for example, 'functional foods'	wide range of current food stocks, primarily well recognized the higher-market value products
ecosystem support	closely genetically tailored stocks for habitat support or enhancement; cryopreserved materials to maintain biodiversity, potential use in carbon management	wide range of species and habitats, though requires protocols and funding commitments
raw materials/bio-feedstocks	a range of chemical/pharmaceutical 'natural' products—proteins, enzymes, structural materials from natural or genetically engineered aquatic organisms	mainly from simple organisms—plankton, etc., capable of high yield and simple extraction—often in high rate photosynthesizing systems extracts from other organisms/body organs may be used
recreational	aquatic organisms of interest for aquarium or angling, and facilities associated with them; tourist products—display and interpretation centres, etc.	development of new products, varieties, improving access and involvement; particularly around urban areas and tourist locales

of refractory compounds such as dioxins and PCBs in the food chain have also drawn adverse comparison with modern intensive agriculture and will not enhance the product position in the consumer's mind. The emergence and impact of generic 'green' values among consumers varies in different markets, though heightened environmental awareness is now more widely observed (Wessells 1998; Aarset *et al.* 1999). While consumer concerns for responsible consumption of wild species have been limited, once the implications of consumption are established, awareness will increase in respect of other species and/or stocks and would extend to aquaculture (Young *et al.* 1999). The issues involved may vary, representing a mix of concerns for conservation, sustainable management, impacts on bycatch, use of critical resources, social and environmental impacts, contamination risks, and food safety. Examples in the aquaculture sector include concerns about social and environmental impacts of farmed tropical shrimp production (Bundel & Maybin 1996; Gujja & Finger-Stich 1996) and environmental impacts and welfare issues involved in intensive culture of salmon and other fish species (Young & Muir 2002*a*).

The depth of consumer understanding of the impact of consumption remains variable and even among more committed groups considerable gaps in knowledge may exist (Aarset *et al.* 1999). While aquaculture may be thought of

Table 9. Scale economy/aggregation factors.
(Source: developed from Muir (1995).)

factor	implications/effects
site locations	impose a natural constraint on unit scale, but technical change acts to increase outputs—better growth, survival, environmental control
direct/indirect cost structures	demonstrate significant efficiency gains towards limits of individual sites and management structures
fiscal/financial	taxation and reinvestment incentives stimulating increased capacity and productivity; regional development support
integration	efficiency gains through, for example, linking hatcheries, ongrowing, marketing
acquisition	different management, finance and site conditions leading to varied commercial performance, and hence opportunities for takeover and capital write-down
management systems	development of effective management systems and staff teams increasing investor confidence in good performers

as an alternative to many overexploited stocks, the dependence of many carnivorous species on feeds produced from other, sometimes overfished, low value species will not comfort many consumers (Naylor *et al.* 2000). However, determining that source feeds for aquaculture come from sustainable fisheries and/or agricultural production may require awareness and commitment beyond many current consumers. Nevertheless, they may increasingly expect that such issues are considered by supermarket buyers, and that they can trust them to honour such concerns. Supermarkets, in turn, are increasingly prepared to seek competitive advantages in being able to offer such reassurance.

A related interest concerns 'organic' aquaculture, where products and production methods are desired to be as 'natural' as possible, and where added attractions of greater biological diversity may also be important. While organic products are likely to receive increased attention, very little is currently produced in aquaculture, though national regulations and international guidelines are being introduced to promote production practices congruent with organic agriculture (DEBIO 1996), and the IFOAM (International Federation of Organic Agriculture Movements) has recently developed international guidelines for organic aquaculture, although not without conceptual and practical issues to resolve (Bousquet 2002; Aarset *et al.* 2004). Owing to production environments, technology features and the spatial distribution of producers and consumers, organic aquaculture producers might be both larger scale and more export-oriented than organic agricultural producers, though perhaps smaller than non-organic competitors. However, without supranational standards, and with a variety of labelling schemes, different national standards may reflect more localized interests (e.g. producers versus environmentalists), with varying species and enterprise diversity (Beveridge *et al.* 1998). Also related to this is the possibility of developing 'fair trade' products in aquaculture, for which there is a current interest in opportunities for linking artisanal producers in developing countries with more discriminating consumers in international markets. However, the organizational and logistical problems of linking diverse producers in poorly controllable aquatic systems with short shelf-life products meeting consumer interests in good quality products with a good ethical content are considerable.

8. THE CHALLENGES OF SUSTAINABILITY

The aquaculture sector depends on a wide range of inputs, with a similarly wide range of outputs and impacts. In more intensive forms in particular, adverse effects can be identified which in the longer term might jeopardize the resource base on which the industry depends. Other forms of development can also have a significant negative impact on aquaculture, and remove otherwise useful and valuable opportunities for food production. While such problems have often taken second place behind the greater benefit of economic growth and improved supply of high-quality food, there are increasing concerns about the balance between environment and development (Roberts & Muir 1995; Barg & Phillips 1997; NATS 1997). These in turn increasingly call into question the simpler production-led approaches to sectors such as aquaculture and require approaches in which the social and environmental context is more clearly expressed. Thus, while food-supply aims might call for increased or better targeted production, there may be little benefit if this is at the cost of seriously impaired natural resources, and a longer-term failure of their support.

The United Nations Commission for Environment and Development Conference of 1992 marked significant political recognition of the human economy and the environment and the entry of sustainable development into political strategy, planning objectives and management action. Most definitions suggest as core issues: (i) futurity—concern for the well being of future generations (intergenerational welfare); (ii) equity—concern for equity for the current generation (intragenerational welfare); and (iii) environment—greater emphasis on the environment. A basic concept also describes general categories of capital stocks—of natural resources, manufactured capital and human or societal welfare, which interact and whose quantities and qualities would be sought to maintain or improve (Roberts & Muir 1995).

The concepts of sustainability have specific focus in fisheries and water resource sectors, and may in turn change perceptions of desirable forms of aquaculture development and management. However, while sustainability can be broadly described, its implications for aquaculture still need to be clarified, to define criteria by which current activities could be operated and new developments specified. Most simply, sustainability might mean that an

Table 10. Technology development: the case of marine aquaculture. (Source: developed from STAQ (2004).)

technology direction	issues addressed	issues remaining	projected development
continued growth in near-shore cage aquaculture	development without further environmental degradation	most to some degree	gradual expansion, significant growth in some areas; more emphasis on coastal zone management and integrated activities
development and uptake of offshore farming	local coastal zone impacts much reduced	higher cost, greater risk, to facilities and to personnel	gradual investment in more exposed sites. major offshore farms by 2010, potential for substantial volumes by 2015–2020
onshore closed recycle systems	nutrient control, escapees, localized impacts, wildlife interactions, disease control	market acceptance, high construction cost, high energy, service charges	for high value species/stages only, unless major efficiency gains, energy costs greatly reduced, GM technology viable and/or much greater restrictions on cages; development horizon probably well beyond 2010
onshore integrated aquaculture	localized impacts, ecological efficiency, reduced nutrients	disease control, land access, predator control, therapeutic use	in sub/tropical countries with low-lying coastal land; products by 2010 but overall production in low '000' t by 2020
free-range aquaculture, hatchery restocking, habitat enhancement, feed attractants and training to enable easy capture fishing	nutrient/ecological efficiency, localized impacts, use of existing fishing vessels and skills	legal obstacles, need to prove technology and 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 tonnes by 2050

activity can continue or a resource be available for at least the medium-term, and is not associated with rapidly depleting inputs. For aquaculture-related projects, the issue might also concern how much it might continue to depend on external (e.g. development) support. More strictly, sustainability would require no diminution of future potential, and provide current-day equity; it may focus on maintaining, and if possible increasing capital stock and ensuring the widest possible access. Such a structure might then allow for depletion of one or more capital stock elements if matched by gain in other areas, and may define non-transferable areas or issues, specified by socio-political choice.

(**a**) ***Sustainability indicators***

To translate this into policy for aquaculture, with strategies for renewable and non-renewable resource use, infrastructure and physical facilities, and social and economic benefits requires both a local and a global perspective (Stewart 1995) and have increasingly been set out in broad guidelines (e.g. FAO 1995, 2001; NATS 1997). With an important non-marketed component to be addressed, in assessing issues of natural and social capital, environmental economic techniques may be employed, though methodologies are currently imprecise if not contentious (Muir *et al.* 1999*a*). A more practical approach may be to use indicators (Azar *et al.* 1996; Costanza 2001), to determine if development and management choices are likely to improve equity and natural resources, or to diminish them. Sustainable food production may be defined as successful management of resources and ecosystems to satisfy changing human needs, conserve natural resources and maintain or enhance the quality of the environment.

In aquaculture, efficient systems requiring fewer inputs and producing wider benefits and fewer wastes could be expected to be more sustainable. Priorities could include:

(i) avoiding irreversible effects, leading to a permanent loss of resource value;
(ii) using non-renewable resources only when an explicit trade-off can be recognized;
(iii) maximizing efficiency of use of renewable resources, subject to present-day financial constraints;
(iv) considering areas where aquaculture or its techniques can offer positive benefits in the wider context, fo example, biodiversity, reduced pressure on key hunted stocks.

An outline indicator structure is shown in table 6, developed initially for salmon and mussel culture.

More detailed indicator systems are currently being developed, borrowing partly from concepts set out for capture fisheries in association with the FAO Code of Conduct for Responsible Fisheries (FAO 1995), but also using structures for local, meso-level and global-level indicators, and incorporating additional features of policy and institutional capacity, and indicators of stakeholder involvement. Related approaches, using more specific numerical parameters, are also being developed using multiple-criteria analyses (Gompiero 1997; Stevenson *et al.* 2003) and use is being made of Delphi analyses to

Table 11. Strategic approaches to development.
(Source: developed from Muir & Young (1999).)

parameter	present state	minimum condition	desired state	optimum condition
policy environment	(example)			
R&D context	disorganized, weak	aware, better funded	focused, well funded	highly organized
environmental	unregulated/negative	regulated, functional	protective, supporting	highly managed
investment	uncertain, negative	clear, definable	positive, supportive	strongly supportive
social	negative/threatened	aware, progressive	supportive, positive	strongly supportive
production context	(example)			
total output	20 000 t	20 000 t	40 000 t	80 000 t
species produced	5	5	8	16
number of farms	300	300	500	800
first sale value	$50 m	$45 m	$100 m	$250 m
value added	$60 m	$40 m	$120 m	$200 m
social context	(example)			
employment	5000 FTE	5500 FTE	10 000 FTE	20 000 FTE
secondary benefit	limited, uncertain	more established	established, diverse	widespread
human resource	owner/unskilled	more skills, wider owned	skilled, widely owned	highly skilled, innovate
price/consumption	high, wealthier	lower, middle wealth	all ranges	all ranges, poorest
access	wealthier only	wider range	better access for poor	access and transforms
vulnerability	high production risks	managed risks	limited risks	very limited risks
system factors	(example)			
onshore	non-existent	trialled, understood	viable, invested	profitable, expanding
inshore	small-scale inefficient	rationalized, viable	expanded, developing	significant productive
offshore	non-existent	trialled, understood	viable, invested	profitable, expanding
seed supply	(example)			
origins	wild caught only	5% hatched seed	90% + hatched seed	all hatched seed
brood maturation	caught in wild	in culture systems	readily available	fully managed
manipulation	untested	basic principles	normally possible	highly controlled
larval rearing	(example)			
husbandry	unknown	basic principles	routinely known	highly efficient
feeding	basic biology	positive trials	controlled, effective	high performance
survival	0%	20%	70% +	90% +

Table 11. (*Continued.*)

parameter	present state	minimum condition	desired state	optimum condition
ongrowing	(example)			
systems	traditional	design analysis	efficient systems	performance optimal
feeding	ad hoc, trash fish	basic pellet diet	efficient pellet diet	high performance diet
disease	unknown	basic understanding	adequate control	negligible impact
control	minimal	principles understood	routine husbandry	highly tuned
market/product	(example)			
awareness	limited/traditional	aquaculture known	quality understood	widely appreciated
availability	poor, irregular	basic supply	regular supply	widely available
product forms	traditional, unsized	basic standard form	range of forms	highly flexible
quality control	non-existent	principles understood	regularly applied	highly specified
market promotion	not present	basic structure	routine application	targeted, proactive

explore constituency-based perspectives on sustainability (Bunting 2001).

(**b**) ***Sustainable livelihoods and aquaculture***

As a means of exploring and explaining sustainability issues, particularly in a rural development context, and to provide an effective systems-based framework for setting out more holistic approaches to development needs and interventions, the concept of SL has been supported and promoted by the UK Department for International Development (DFID) (Carney 1998). This has, as its antecedents, the work such as that described by Chambers & Conway (1992) and Scoones (1998) in which needs and constraints of communities and individual farmers and households are recognized as an essential starting point for interaction in development, for determining where constraints arise, and for defining research priorities. The SL framework identifies five asset groups or sustainability capitals, i.e. natural, social, human, physical, and financial capital. It identifies sources of shock and vulnerability with respect to household or community capital stock, describes the role of policies, institutions and processes in public and private sector actions in interacting with and mediating ownership, management and access to capital stocks. It provides a locus for development intervention—via various 'entry points' whereby interests of poorer and more vulnerable groups can be identified and secured, and means found and processes identified to improve livelihood conditions. The system so developed can be set out at a range of socio-political levels—from household to national economy and linkages identified between them. It can also be extended to describe the social and economic contexts in which peri-urban and urban communities exist, and the ways in which development interventions may be identified and implemented.

As an increasingly important element in rural economic output, in food supply and in urban markets, aquaculture has naturally found a presence in such frameworks. In turn, these have allowed a more specific understanding of the development potential of aquaculture to meet local and national development objectives (Ahmed & Lorica 2002), and to contribute to meeting international goals of poverty reduction while maintaining natural resource capacity and quality. Here, technical knowledge and its dissemination through traditional channels is valuable, but not sufficient, and better understanding is being sought in identifying access to resources, skills and opportunities, market dynamics associated with changing supply bases, and interactions between changing features of rural and urban demography, employment, income distribution, purchasing power and consumption preference. At the same time, many of the more informal means by which poorer households had been able to benefit from aquaculture, or the release of hatchery-reared stocks into various water bodies, for example, by sharing harvests in exchange for labour, by obtaining access to lower-value small indigenous aquatic species as 'bycatch' in aquaculture systems and by cropping fish in micro-harvests from rice-fields, are now changing. With increased commercialization following access to urban markets, these may no longer provide the same levels of support (FSRFD 2003).

Table 12. Constraints to development and uptake of aquaculture.
(Source: developed from Muir (1995).)

area of concern	issues	possible strategies
past research strategies	scope too narrow; primarily zoology and basic technology, intensification; neglect of social and environmental context, short-term in response to funding	*post-hoc* analysis, lessons learned; focus towards integrated approaches
present state of research	wide variation in capacity between regions; specific needs of different types of development poorly appreciated, inappropriate resource allocation, lack of understanding of farming systems; need for integrated strategies, multi-disciplinary staff resource; lack of long-term funding support, operating funds; low motivation, lack of competition, dynamism, quality of training	improved procedures for research strategy, selecting priority areas, multidisciplinary approaches, appropriate protocols, cooperation mechanisms and means to integrate plans, skills and outputs; more focus on operating expenditures, improved selection, training, motivation, evaluation, staff conditions, external communication; programme funding continuity
disparities in distribution of knowledge	wide regional variation in basic knowledge and techniques available, impeded flow of knowledge, lack of competition, interchange, communication; need for evaluation, need wider participation with developed country activities	better communication, meeting, exchanges of ideas, network access, external evaluations of work programmes, better regional mechanisms, develop high standard regional scientific journals
the use of research	communication gap between public sector institutes, universities, production sector, inappropriate dissemination mechanisms, top-down approaches, unrealistic demonstrations	better fora for exchange of ideas, participation; validation under real field and economic conditions, etc; mechanisms for joint financing of research, strengthened user/producer groups, systematic procedures to evaluate development
institutions	resources spread across too many institutes, emphasis on capital structures, low priority to innovative research; limited term funding for regional institutions, problems of funding in general for operation and for wider networking	develop national entities, with clear priorities co-ordinated linked centres, access to international cooperation; formal structures for regional cooperation and specific action programmes for innovative research

9. FUTURE DIRECTIONS

Aquaculture has had a long history and is in many cases linked with very traditional forms of production, associated with local resources and skills (Beveridge & Little 2002). While its potential can be widely understood and its dynamic of growth together with evident scope for demand, suggests significant future growth and change, these cannot automatically proceed from existing scientific interest and changes in production technologies. Forward projections need to take account of likely changes in the capture fishery, and changes in population, income distribution, *per capita* fish consumption and consumption preferences, together with the real price levels at which aquaculture product of appropriate quality can be made available, in the face of increasing resource competition. A number of synoptic overviews have suggested that regional- or global-level natural resources are not an immediate constraint (e.g. Aquilar-Manjarrezz & Nath 1998; Tacon 2001), particularly for semi-intensive production, though there is specific evidence of local overloading of environmental capacity and hence limitations of further production potential (Bhatta & Bhat 1998). Considerable concern and controversy also surrounds the potential for social inequity (Stonich *et al.* 1997; Deb 1998; Environmental Justice Foundation 2003) the potential impact of technology advances on artisanal producers (Clarke & Mair 1998), and the wider system impacts of intensive aquaculture development (Ellis & Weir 1997).

(**a**) *Price and species choice*

Regarding interaction between aquaculture and capture fisheries, it is important to note the disparity in price and cost of production, and the nature of consumer demand, in which a strong inverse price–quantity relationship can be described in most markets (Muir & Young 1998). As shown in figure 3, in European markets, *ca.* 63% have a first sale price below 1 kg^{-1} and 85% below 2 kg^{-1} Separating capture fisheries from aquaculture shows that capture fisheries are especially dominated by lower value products with 73% of production below 1 kg^{-1} and 97% below 2 kg^{-1}. For aquaculture, this is reversed, with *ca.* 96% of produce priced at over 2 kg^{-1} and 85% in the 2–4 category. A ‘supply pyramid’ can be described, with 85% by weight priced below 2 kg^{-1} at first sale value, with most of the remainder in the 2–5 kg^{-1} range, in which aquaculture is the primary supplier (STAQ 2004). While such disparities are not so strong in other markets, for example in South and East Asia, where price differentials between aquaculture and fisheries products, particularly in freshwater species, are not so marked (FSRFD 2003), the supply–price—investment interaction needs to be explored further (see Ahmed & Delgado 2000). Issues such as future income distribution will be critical in determining the affordability of aquaculture product, and hence the investment and resource competitive potential for growth.

Changing consumer preferences (figure 4) linked, in turn, with changing price structures will also influence the distribution of consumption. This will further be associated with the scope for developing new product forms, and the relative merits of particular capture or culture stocks in meeting needs as a raw material. In this respect, the replacement potential for traditional capture stocks such as cod may not necessarily involve the aquaculture of those species. The primary set of market attributes is simply that of white flesh, with relatively little taste or odour, a reasonable flexibility of portion shape and size and the ability to blend with sauces and hold coatings of various forms. Thus species like tilapia, which can be grown semi-intensively with far less complex and demanding resource inputs than those for marine carnivores, may have much more potential, and may offer important international trading opportunities, particularly for developing countries (Young & Muir 2002*b*). Atlantic salmon, though more demanding of resources has also made substantial inroads in new product formulations, and is increasingly being seen as a versatile food component in a range of value added forms.

Associated with this is the extent to which focus is given to improving production characteristics of existing ‘core’ species such as carp, tilapia, salmon, trout, catfish, shrimp and mussels, or to extending the range of culturable species. Related to this, in turn, is the extent to which it might be expected that genetic technologies could be expected to enhance production performance and efficiency in culture conditions, and the level of acceptance this might have in consumer and regulatory terms. Table 7 presents comparative scenarios based either on diversifying species or on product forms, with different levels of genetic-technology-based production efficiency gain.

(**b**) *Non-traditional functions*

There is also wide interest in the extent to which aquaculture may be used for non-traditional purposes, i.e. beyond the supply of food or other simple raw materials. Though these sectors are currently relatively insignificant, or the role of aquaculture and its associated skills and technologies relatively poorly developed, table 8 summarizes some of the areas of current development and their potential. It is important to note that few of these will be recorded in traditional formats for output and value, and in the latter terms in particular, values not associated with direct market consumption may be very significant but potentially under-recognized.

(**c**) *Commercial structures and technology choice*

Regardless of the location and production aims, the nature and scale of production is also likely to change, as larger production units and commercial entities gain competitive advantage in terms of technical efficiency, production costs and market power (Muir 1996; STAQ 2004). Table 9 outlines the primary factors underlying these trends, most of which can be observed in most aquaculture sectors internationally. While salmon aquaculture has been the best documented, similar trends are found in other intensive aquaculture sectors. While artisanal, smallholder-based aquaculture still represents a large part of global production, and remains the focus of considerable development interest (Harrison 1997), there is also increasing evidence of larger, more efficient producers with greater market power becoming more dominant. If only because they have greater scope for investment and expansion, and in more integrated markets, there may be increasing concern for the future of smaller-scale units, unless organized in producer cooperatives (Hough & Bueno 2002).

To substantially increase the more intensive forms of aquaculture, on which most recent investment has been based, two key constraints need to be addressed. The first is the use of marine fish oil and fishmeal and while present rates of growth can be sustained well into the present decade (Barlow & Pike 1997), alternative protein and lipid sources would be needed (Hardy & Tacon 2002). The second is the environmental capacity of production zones, whether for intensification of existing production or in creating new systems. There is evidence, however, of good scope for intensifying production in many sub-tropical and tropical areas, though locally, water exchange and replacement may be a specific constraint. In some cases, changes in agricultural land use and farming practice may be constraints (Nickerson 1999) and further and more strategic approaches to integration may be appropriate. For more intensive aquaculture, coastal zones are the least heavily loaded in terms of production per land area or water exchange and offer by far the largest potential environmental capacity (Dolopsakis 1996). Technical options (table 10) include expanding existing systems in inshore areas, developing offshore, using onshore pumped or recycled units, onshore integrated pond systems and free-range farming.

However, the constraints for each are considerable. Land-based farms are only likely to be viable for high value species unless energy and production 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 regulation or market pressure.

Disregarding the gains potentially available through genetic technology, improvements in efficiency as a whole are likely to be incremental, as many gains have already been captured, particularly in more intensive sectors. Key areas are in feed efficiency, the further reduction in mortalities due to disease, predators or escape and better growth rates and use of facilities. For high-value marine finfish and crustacea, the greatest potential gains are in the hatchery phase, where mortality rates are very high and the potential for genetic management through multiple generation cycles is currently limited. Thus, although species such as cod and haddock have culture potential, high hatchery costs limit their market scope to only the higher price niches. The production costs of more efficient systems are more likely to become dominated by the main variable costs of seed and feed, though production cost profiles will vary with systems and species. In broad terms, nutrients will increasingly dominate production costs in more efficient non-autotrophic systems, and systems of this sort will be expected to dominate lower-cost production sectors.

(d) *Global production scenarios, human development and poverty alleviation*

New technologies will affect efficiency and cost of production and hence comparative economics of different systems. A changing balance of cost structure might change preferences for particular species and strains, for specific technologies, and for particular locations and sites. There may also be major geo-economic changes in preferred producing areas and systems and a corresponding change in the nature and location of resources involved. This is not a short-term effect, given typical investment cycles, but would develop over longer periods, perhaps decades (Muir 1995; STAQ 1996). Most obvious in more internationally competitive sectors, recent examples include: (i) the rise of Chile as a major producer of Atlantic salmon; (ii) the rapid development of offshore cages for sea bream in the Mediterranean; (iii) the expansion of channel catfish farming in the USA and increasing competition from Vietnam; (iv) the increase of Asia and Latin America in supplying tilapia to North American markets, and within countries; (v) the gradual shift of production from one region to another, as for example in Thailand (clarias catfish and shrimp) and the USA (channel catfish) as comparative advantages become clear.

Regional growth in aquaculture, much dominated by China in recent decades, according to recorded figures, is likely to shift with changing opportunity, international investment and a widening and more mobile skill base. There will be an increasing shift towards areas with good natural resources, the potential for lower cost production and/or access to growing international or regional markets, and a strong emphasis on economic growth and trade (Muir *et al.* 1999*b*). Countries such as Brazil, Argentina, Mexico, Australia, and those such as South Africa, Mozambique, Uganda and Zimbabwe, depending on political and economic stability (Hecht 2000; Anon. 2001), can all be recognized as having significant potential. However, many existing areas are also likely to grow significantly, through a combination of incremental expansion and rationalization, efficiency gains and higher productivity (Alam 2001; STAQ 2004). Much will depend on how aquaculture products interact with fisheries products (Bene *et al.* 2000), how strategies evolve for fisheries governance, and the implications for output and markets (Allison 2001; Pauly *et al.* 2002).

In international policy terms there are likely to be several contradictory issues, including the balance of interest between national self-sufficiency and food security, using natural resources for national food supply and local employment, and the opportunities for export earnings, with the common implications for income distribution, environmental negligence and possible social inequity. These issues are increasingly likely to feature in trade disputes (Anon. 2003) and a wider range of national legislation for issues such as food safety or ‘bio-terrorism’ in major markets with strong production interests may be interpreted to constrain trade (Anon. 2002; Woodhouse 2003).

While price impacts will be an important determinant in the potential for aquaculture to address poverty and improve food supply, there are useful parallels with the agriculture sector (Pretty *et al.* 2003) and access to resources, skills and markets will be key elements in development, food supply and food security (FAO 2002*b*). Links between rural economies and those of the increasingly politically dominant urban centres will be critical in determining the nature of aquaculture development, food availability for local households and poorer community groups (e.g. Thilsted *et al.* 1997; Ellis & Sumberg 1998). The potential for development to meet both income and food supply needs will be a particular challenge (Stonich & Bailey 2000; FSRFD 2003) and focus would be required on approaches which specifically meet the needs of the poorest groups and further provide them with the means to improve their opportunities over the longer term (Lewis 1997). The significance of gender in terms of resource access, social inclusion and economic opportunity will also be critical (DFID 2000; Setboonsarng 2001). In these respects Prein & Ahmed (2000) in an overview of integrated aquaculture–agriculture in Africa and Asia proposed that these systems would offer better food security, diversity of income, and local household benefits. However, practical issues of resource access, labour availability and production risk would also need to be considered (Setboonsarng & Edwards 1998).

(e) *Research and development strategies*

The aquaculture sector has derived inputs from a range of sources, mixing academic biological research, agricultural and fisheries technology, developed in an essentially *ad hoc* manner. The use of research goals in terms of productivity, development impact, financial performance or specific factor usage, had been relatively uncommon, though in development projects at least, the application of logical frameworks has provided some structure (Muir 1995). The small scale of the sector and its relatively unsophisticated origins has often made it difficult to define strategic research issues and development priorities. Though assumed economic importance in a number of areas, it is itself unlikely to become a major source of technical innovation, owing to:

(i) the limited capacity of individual producers, and lack of enthusiasm for collective approaches;
(ii) increased competitive pressure reducing opportunities for independent enquiry and focusing innovation and management targets towards maximizing productivity;
(iii) the dynamic of research functions as being independent of aquaculture industry promotion;
(iv) the changing roles within company structures, and the difficulty of retaining a medium-term research presence in a rapidly changing commercial environment.

As outlined in table 11, development strategy frameworks could be employed to define the areas in which a particular sector could be developed, and research targeted to meet essential priorities.

As this framework indicates, issues could cut across a range of disciplinary boundaries, and may require an integrated approach with suitable indicators of progress. Here, the uptake and use of knowledge, particularly in meeting international targets for food supply and poverty alleviation, has been recognized as an important constraint, with concern for the effectiveness and impact of research investment. Table 12 summarizes key issues and constraints, and identifies possible ways to improve outcomes. An important challenge lies in combining disciplinary perspective with good effect (White 2002) and in recognizing the wider institutional context in which development will take place (SEAFeeds 2003).

(f) *Conclusion*

If aquaculture is to develop and provide for current and future needs sustainably, it will require clear objectives and a well developed policy. At current growth rates of some 11% per annum, by 2030 more than half the world's aquatic food supply could derive from aquaculture (Browdy 2002). Depending on the extent to which capture fisheries can be sustained, this could imply real improvements in *per capita* food supply, and significant gains in global human welfare. However, more natural resources would be employed to achieve this, traded for physical/economic capital, and in turn human and societal benefit. There could also be scope for diversity; i.e. activities which measure poorly on sustainability criteria may be compensated by others which produce a 'surplus'. Three major objectives could be identified, broadly related to the major capitals of sustainability analysis:

(i) appropriate conditions for growth, whether determined by market development, technical change, or institutional support (stock and quality of economic/manufactured capital);
(ii) social equity, either directly, in allowing all sectors of society to consume aquaculture products or even guaranteeing food security, or indirectly, in bringing other benefits which improve overall opportunities for food supply (stock and quality of human/social capital);
(iii) production should be carried out efficiently, while delivering its benefits with well managed use of and minimal impact on natural resources (stock and quality of natural capital).

In summary, the efficiency and footprint of the aquaculture sector as a whole will be determined not just by technical efficiencies in the intensive sector, but also by the overall balance of production intensity, internal recycling (i.e. system closedness), resource and transport energy and environmental impact (Muir 1996). The latter will also be influenced by the extent of remediation (Stevenson *et al.* 1999) and the degree to which aquaculture itself could contribute to environmental compensation. The aquaculture industry is likely to remain relatively diverse with individual sub-sectors undergoing cycles of expansion, consolidation or stagnation. Relative economic performance will be the primary determinant of uptake and expansion, influenced by regulatory policies and consumer preferences. Over the longer term, more comprehensive data collection concerning all aspects of aquaculture and resource use combined with market traceability systems and more effective perspectives of analysis, also has the potential to form the core of an integrated information-rich approach to aquatic system management, better approaches to food safety and environmental protection, together with clearer and stronger policy impact.

ENDNOTES

[1] Formerly ICLARM—International Center for Living Aquatic Resource Management.

[2] International Food Policy Research Institute.

[3] This category continues to be used in FAO reporting of production, though in view of technical problems of defining brackish-water production environments many observers simply use a binary definition of inland (primarily fresh water) and coastal (saline water) aquaculture.

[4] Based on chromosome manipulation to create sterile and/or single-sex stock; also using modified parents (e.g. masculinized female stocks) to produce single-sex offspring by normal methods. Most techniques aim to manipulate parent stock rather than stock for production.

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GLOSSARY

ADD: acoustic deterrent device
FCR: food conversion ratio
GIS: geographical information system
SL: sustainable livelihoods