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ORIGINAL PAPER

Effect of feed and feeding in the culture of salmonids on the marine aquatic environment: a synthesis for European aquaculture

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Abstract While marine aquaculture has grown rapidly, so have concerns regarding the environmental impacts caused by the industry. In particular, increasing discharges of solid and dissolved fish excretions, nutrients and therapeutic chemicals have coincided with greater public awareness of the possibility of environmental damage. This has stimulated a number of criticisms, drawn from a wide spectrum of interests, ranging from the use of natural fish stocks to produce fish meal for aqua feeds to the effects of enhanced nutrient input on the coastal marine environment. The present study reviews available information on the environmental effects of feeding practices in salmonid aquaculture in Europe. Accumulation of waste food and fish faecal material results in changes in the sediment under fish cages, characterized by a low redox potential, high content of organic material and accumulation of nitrogenous and phosphorous compounds. Although significant environmental impacts have been reported in the literature at distances of up to 100 m from the cages, in general such impacts are reported to be localized to within 20–50 m around the cages. For farmed salmon and trout, mass balance models have been developed for nitrogen and phosphorus, indicating that 50% of the nitrogen and 28% of the phosphorus supplied with the food is wasted in dissolved form. The maximum nutrient release can be estimated from the hydrographic conditions in the immediate vicinity of the farm, such as water volume, tidal water exchange and currents. At present production levels, improvements in the feeding efficiency and

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feed quality of aquafeeds could reduce waste and consequent environmental impacts.

Keywords Aquaculture · Environment · Feeding · Feeds · Fish meal

Introduction

According to FAO statistics, aquaculture's contribution to global supplies of fish, crustaceans and molluscs continues to grow, increasing from 3.9% of total production by weight in 1970 to 27.3% in 2000 (FAO 2002). Based on these statistics, aquaculture is growing more rapidly than all other animal food-producing sectors. Global fish production from capture fisheries and aquaculture provides more than 15% of the animal protein consumed by the world's human population (FAO 2002).

Aquaculture production in Europe has grown to become a significant industry over the past decade and has partly compensated for the decrease in capture production due to dwindling natural stocks. In 1999, it represented 31% of the total value of fishery production (the summed value of landings in the ports of Member States plus aquaculture production) (European Commission 2001). At a global level, the European Union (EU) represents approximately 3% of world-wide aquaculture production (European Commission 2002). The largest aquaculture producer in Europe in 2001 was Norway (Fig. 1). In terms of volume of production there are four other countries in Western Europe, aside from Norway, which are major producers, namely Spain, France, Italy and the United Kingdom. In Eastern Europe, in terms of volume of production, Turkey is the major producer (Fig. 1; Fishstat 2001). The ranking of the most important commercial species in terms of aquaculture production volume (tonnes) and value (in euros) in Europe is summarized in Fig. 2 (2001 data, Fishstat). The most important species in terms of volume and value of production for aquaculture is the Atlantic salmon (*Salmo salar*) (high market value but also high cost of production), while the species with the second highest levels of production are mussels (in terms of volume) and seabream and seabass (in terms of value) (Fig. 2). It seems that high production (volume and value) is associated with intensive farming of marine fish species (salmon, while the highest production purely in terms of volume (i.e. mussel farming) is associated with lower market value.

Of the total world aquaculture production in 2001, 37% was in the form of finfish and crustacean species, the production of which is dependent upon the supply and use of external off-farm nutrient inputs in the form of compound aquaculture feeds (Tacon 2003). At present, the production of aquafeeds for finfish and crustacean species is highly dependent on capture fisheries for sourcing essential dietary lipids (in the form of fish oil) and high-quality marine animal proteins (in the form of fish meal). Generally, recommended dietary protein levels for crustacean species vary from 30 to 57%, and recommended dietary lipid levels range from 5 to 8% (D'Abramo et al. 1997; Shiau 1998; Mente 2003).

Feed development may need to place increased emphasis on the efficient use of resources and the reduction of feed waste and nutrient discharge. Research has shown that a significant reduction in the level of incorporation of fish meal is possible without affecting the growth rates or flesh quality in several species of interest to aquaculture in the EU (Kaushik 2003). With regard to the use of fish oil, a

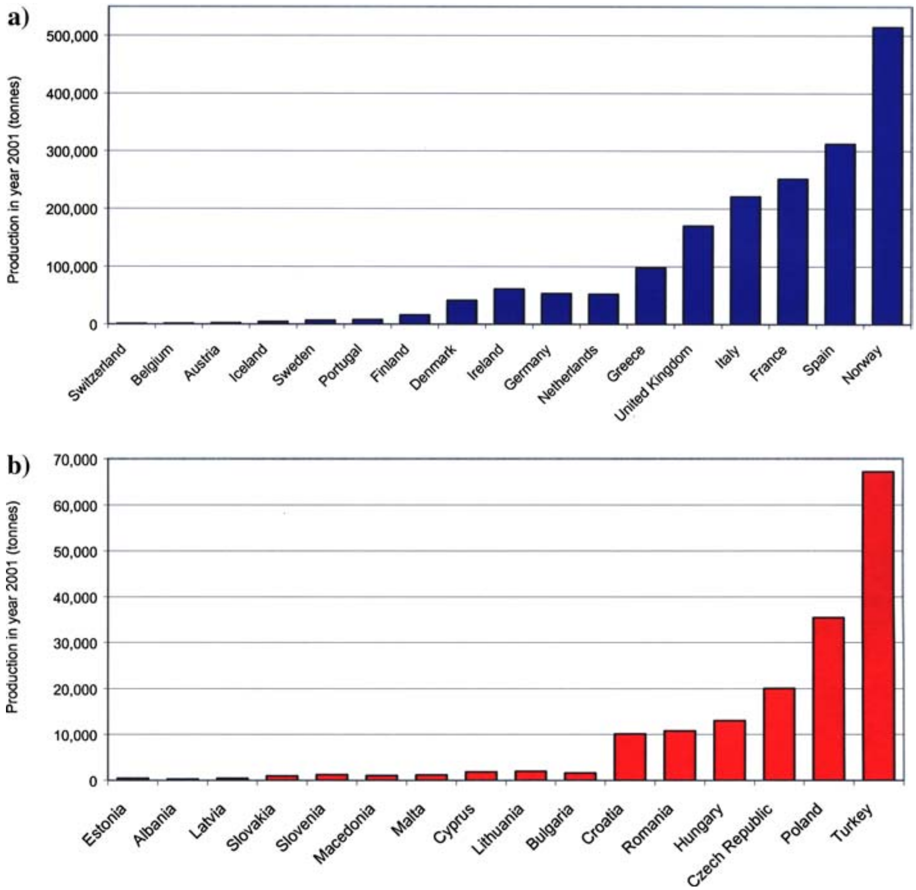

Fig. 1 Western and Central (**a**) and Eastern (**b**) total European aquaculture production (2001). Source: Environmental European Agency (EEA) report: Review of fisheries and aquaculture – a basis for indicator development (http://www.reports.eea.eu.int/Eurostat; Statistics in focus, 2004; FAO Fishstat Plus, 2001. All as available in EEA data service

significant reduction is possible, even in marine finfish culture, without any adverse effect on growth or feed efficiency, provided that the essential fatty acid needs are met (SEAfeeds 2003). Diversification and the use of alternative species for cultivation, or krill and copepods, or discards and by-catch from feed grade fisheries to produce aquafeeds have been suggested as other options to ensure sustainable aquaculture.

While aquaculture has grown rapidly in recent years, so have concerns expressed by aquaculturists, scientists and the public regarding the environmental (Table 1) and social impacts of the industry (ICES 1995, 1999; Gillibrand 2000; Black 2001; Focardi et al. 2005). For example, the accumulation of wasted food and faecal material affects sediment characteristics under fish cages (Hall et al. 1990) such that affected areas are characterized by low redox potentials (Hargrave et al. 1993), high content of organic material (Hall et al. 1990; Holmer 1992) and the accumulation of nitrogenous and phosphorous compounds (Holby and Hall 1991; Hall et al. 1992;

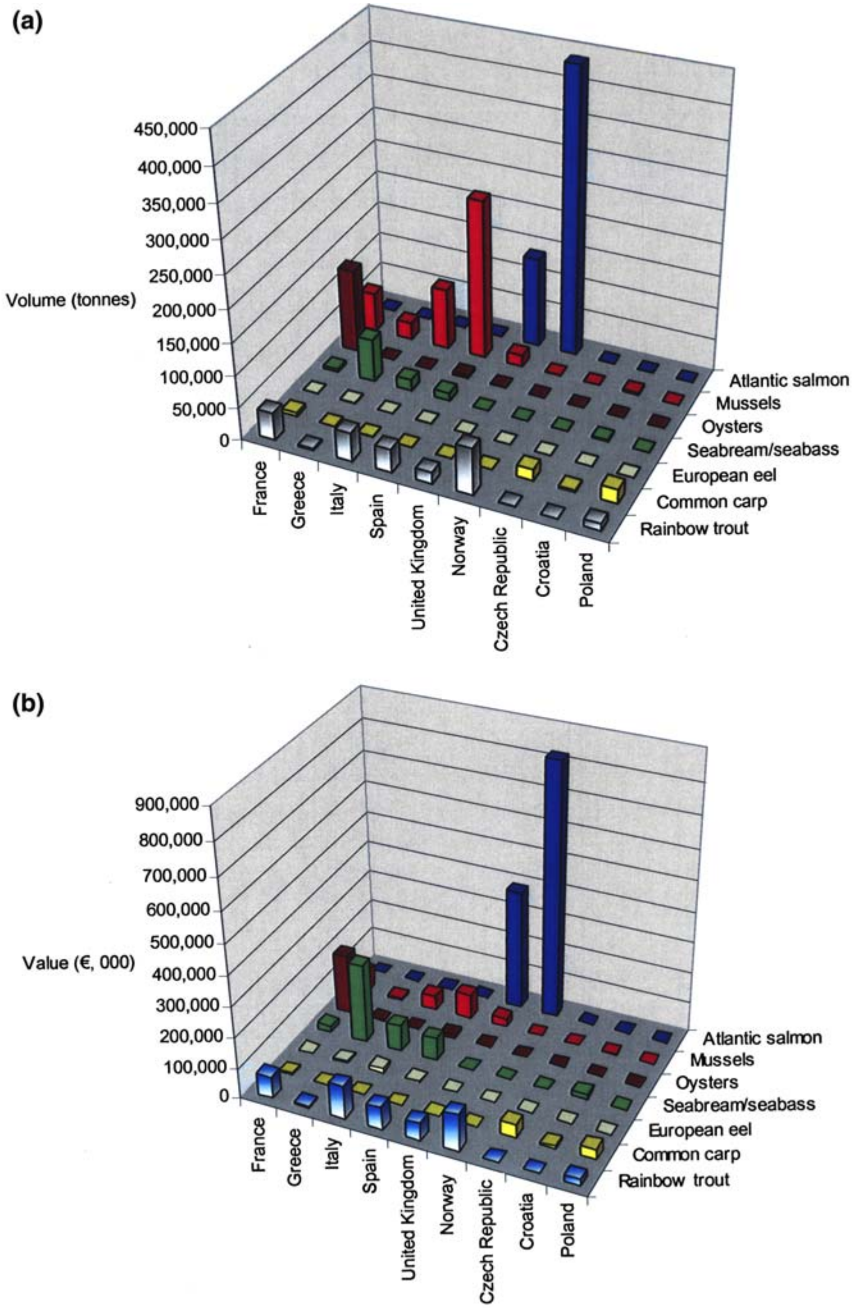

Fig. 2 Main farmed fish species production expressed in volume (tonnes) (**a**) and value (in euros) (**b**) in Europe (2001). Source: Environmental European Agency (EEA) report: Review of fisheries and aquaculture – a basis for indicator development (http://www.reports.eea.eu.int/; Eurostat, Statistics in focus, 2004)

Table 1 Summary of the current main environmental concerns arising from aquaculture operations (modified from Fernandes and Read 2000)[a]

Potential direct impacts	Potential consequences	Management actions
Fishmeal supply is limited and demand is likely to exceed supply in the future	Increased pressure on feed-grade fisheries	Ensure that fishmeal for aquafeeds is sourced from stocks which are within safe biological limits
	Wider ecosystem impacts (e.g. on predatory fish, mammals and seabirds)	Management regimes ensure that the stock remain within these limits
		Substitution by alternative protein resources
Fish oil reach critical supply constraint	Decline	Guidelines for ecosystem-based management
	Wider ecosystem impacts of feed-grade fisheries	Monitoring and enforcement
	Increased incentive to harvest alternative sources	Ensure low levels of hazardous substances
		Research and policy development
Organic enrichment	Impact on wildlife/habitats	Locational guidelines
Nutrient enrichment	Trigger of toxic blooms	Biomass maximum
Chemicals release	Demise of wild stocks	Maximum feed limit
Spread of diseases		Restricted use of chemicals
		Management guidelines (including Codes of Practice/Conduct)
Escapees	"Genetic dilution"	Improved cage design
	Demise of wild stocks	Management guidelines
Interaction with other coastal activities	Visual impacts and conflict with e.g. tourism, recreation fishing, maritime transport	Locational guidelines
		Derive regional/local Coastal Plans and integrate with national Coastal Management Plan

[a]MARAQUA (http://www.biol.napier.ac.uk/maraqua/fern.htm)

Karakassis et al. 1998). These changes in sediment characteristics induce conspicuous changes in benthic communities (Pearson and Rosenberg 1978; O'Connor et al. 1989; Weston 1990; Pocklington et al. 1994). Changes in the benthos are likely to be greatest beneath caged finfish because of high stocking densities and high rates of feed addition to a localized area (Hargrave et al. 1993). Secondary disturbances, such as benthic algal bloom, may prolong recovery after the fish farming activities have ceased (Karakassis et al. 1999). Although significant impacts have been reported at distances as far as 100 m from the cages, and more subtle effects have been found up to 150 m away (Weston 1990), in general, this impact is localized to within 20–50 m around the cages (Beveridge 1996).

Cage farming also results in considerable nutrient release into the water column. For farmed salmon and trout, mass balance models have been developed for nitrogen (N) (Gowen and Bradbury 1987; Hall et al. 1992) and phosphorus (P) (Holby and Hall 1991) which indicate that 50% of the N and 28% of the P supplied with the food is wasted in dissolved form. Seasonal variability in food supply determines the seasonal variability in loss of carbon (c), N and P into the seabed and the water column. In undisturbed temperate marine ecosystems, nutrients are abundant during winter and early spring and are gradually depleted in the surface waters during the warm season, whereas in marine culture-impacted ecosystems most of the nutrient enrichment in the water column occurs during the warm period (i.e. summer and early autumn).

Fish farming wastes contribute to dissolved N and P but not to silica, thereby creating conditions favouring the growth of certain phytoplankton groups, such as flagellates or cyanobacteria (Parsons et al. 1978; Doering et al. 1989), instead of the silicon (Si)-limited diatoms which form part of the classical food web, channelling energy towards higher trophic levels (including fish). Where several fish farms are situated in close proximity, the increased nutrient levels may lead to algal blooms and the depletion of oxygen (Pillay 1992).

Other undesirable environmental impacts of fish farming (mostly documented in relation to salmon farming) may include the genetic contamination of wild stocks by farmed escapees, increased levels of parasitism in wild fish and the environmental effects of chemicals used as antifoulants or to control parasites (Pillay 1992). Costello et al. (2001) categorize chemicals as disinfectants, antifoulants and medicines (including vaccines). Formalin and Iodophors are the most widely used disinfectants in European aquaculture (Henderson and Davies 2000). Antifoulants are, by their nature, toxic to marine organisms. The amounts involved may be substantial—for example, around 156 tonnes of copper were released into the environment from the use of antifouling treatments in salmon farming in Norway in 1994 (Thomson and Side 2002). Although the potential for damage to wild populations as a result of escapes from fish farms clearly exists, the degree of impact is presently not well known. Escapees from fish farms may interbreed with the wild population, resulting in losses of genetic variability, including the loss of naturally selected adaptations, thus leading to reduced fitness and performance (Jonsson 1997; Scottish Executive 2002). The most economically and environmentally significant parasites in Atlantic salmon farming are sea lice, for example, the salmon louse (*Lepeophtheirus salmonis*). A range of veterinary medicines is used to control them (Costello et al. 2001). Sea louse infection can compromise the condition and welfare of farmed Atlantic salmon as well as lead to a higher abundance of sea louse larvae in adjacent waters (Penston et al. 2004). Although they are natural marine ectoparasites of salmon, they feed by grazing on the mucus and skin of salmon and can cause severe welfare problems and create sites for secondary infections such as *Vibrio* species if not controlled (Pike and Wadsworth 2000).

It has been proposed that positive environmental impacts from cage farming also occur (Guastavino et al. 1999). These might include an indirect benefit for the conservation of biodiversity by decreasing pressure on certain wild stocks and habitats, carefully managed reintroductions (e.g. sturgeon) and a positive impact on the overall plankton community (Guastavino et al. 1999). In Greece, the nutrient input from fish farms occurs into oligotrophic waters, and the farms appear to attract wild fish. Machias et al. (2004) concluded that the release of nutrients from fish farming in nutrient-starved systems (oligotrophic environment) has a positive effect on local fisheries with no visible negative change in species composition or biodiversity. In addition, implementation of polyculture systems or the integration of aquaculture with other coastal activities could result in a synergistic reduction of the environmental impact (Newkirk 1996; Brezeski and Newkirk 1997; Troell et al. 1999).

According to Guastavino et al. (1999), four main constraints limit the expansion of aquaculture: market constraints, environmental constraints, diseases and production costs. Reports of wide environmental impacts have recently received a high profile both in the scientific literature and the grey literature (see Ackefors and Olburs 1996; McGarvin 2000).

The present review concerns the environmental sustainability of salmonid culture in Europe and aims to identify and quantify positive and negative effects of fish feed and feeding on the local physical marine environment. The study collates available information on environmental quality in the vicinity of aquaculture development, including data on water quality and marine biota, benthos, and inputs/outputs from aquaculture facilities and other anthropogenic and natural sources. It also reviews the use of fish meals/oil in aquaculture feeds, which results in salmonid culture being protein intensive to the extent of being a net consumer rather than a producer of animal protein.

Methods of quantifying feed wastes

One method of estimating environmental impacts from aquaculture is direct measurement through sampling and subsequent analysis of the water column and the sediment. This usually involves the suspension of traps below the cages and hydroacoustic and video techniques to determine food losses (Beveridge 1996). Direct observation by diving is also used for benthic impact assessment (Black et al. 1996). Such methods have shown that food losses are typically 1–15%, although if feeding with trash fish they can be as high as 40% (Wu 1995). Feed pellets may be rejected by the fish rather than swallowed if they are contaminated in any way or the fish does not feel like eating (Smith et al. 1993).

The development and use of models to estimate and regulate environmental impacts play a key role in assessing the sustainability of aquaculture and the receiving environment. Henderson et al. (2001) reviewed the use of hydrodynamic and benthic models for managing environmental impacts. A mass balance approach can be used in combination with real field and laboratory data. Uneaten food, faecal losses, food conversion ratios (FCR; the ratio of the weight of feed added to the weight of fish produced) and digestibility can be estimated to derive expressions of various wastes, such as for N or P. The result is a budget showing the flow of nutrients from the food offered, the assimilation of food in the fish as a result of growth (metabolism) and the loss of nutrients into the sediments and water column. Wastage of whole pellets may depend on various factors. If pellets are supplied at a rate that exceeds the ability of the fish to eat them or under conditions such that the pellets are not detected as they settle, there will be wastage of whole pellets.

An example for a closed system such as Atlantic salmon is shown in Fig. 3. Nitrogen content of farmed salmon is 3% (on a wet weight basis) (Ackefors and Enell 1990). From this, the amount of N retained in fish as they grow can be calculated. Current salmon culture practice limits waste in the form of uneaten pellets to 5% (Davies 2000). The proportion of input from feed pellets that is lost as particulate waste (e.g. excess pellets plus undigested material) is 15% (Davies 2000). The discharge of faecal matter can be calculated from the amount of feed offered less the waste of uneaten pellets. Dissolved N is calculated as the difference between the amount input of N in the feed and the sum of the amounts in N in particulate waste and fish growth (Fig. 3). Based on the assimilation of all these factors, the predicted total release of dissolved N is 43.35% of the input.

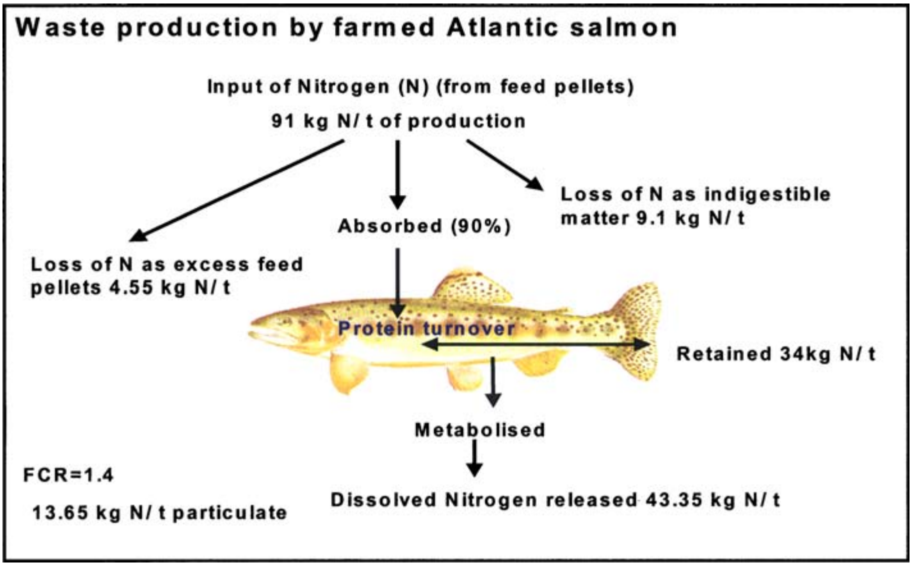

Fig. 3 A simple mass balance model (Davies 2000) to estimate the rate of production of dissolved and particulate nitrogenous waste by farmed salmon in a Scottish Loch (AQCESS project 2000). *Notes*: (1) N absorption, N retention, N losses values are taken from Davies (2000). Input N from feed pellets values and food conversion ratio (FCR) are taken from the data obtained by the AQCESS project; (2) FCR = weight of feed offered divided by increase in wet weight of fish; (3) The retained N is taken as 3.4% N on a wet weight basis; and (4) The dissolved N is calculated as the difference between the amount input in the feed and the sum of the amounts in particulate waste (excess pellets plus undigested material and fish growth)

Davies (2000) reported predicted dissolved N release rates in the range of 35–45 kg per tonne of salmon produced, depending on the details of the stocking, feeding and harvesting strategies adopted. GESAMP (1996) reported values for the rate of excretion of dissolved N by farmed fish of around 75–120 kg N/tonnes of production. If the FCR, wastage from uneaten pellets and indigestibility can be reduced further, it is anticipated that release rate of dissolved N would be reduced to 33 kg/tonne of production (Davies 2000). Further reductions need new technology and additional innovative approaches. In Scotland, Gillibrand et al. (2002) predicted total N discharges (kilograms per tonne) of fish produced and used it to categorize sea lochs on the basis of the nutrient release and input of organic matter on the sea bed. ‘‘Species factors’’ have been developed to take account of the degree to which the rate of production of waste from ‘‘new’’ species differs from that of salmon (Table 2). It seems that the commercial production of halibut (67.1 kg/tonne total N discharged, as compared to 86.9 kg/tonne for turbot) may be possible and could be an opportunity for diversification, although further studies are required on growth rates, feed conversion efficiency and the partitioning of dissolved N between ammonia, urea and other soluble compounds (Davies and Slaski 2002). The deposition of organic-rich waste onto the sediment can be estimated by modelling on the scale of approximately 200 m (approximately the scale on which effects on the benthos are expected to be found). The potential trail of organic waste and its dispersion characteristics/intensity can then be modelled using particle tracking or deposition models, utilizing the settling characteristics of feed and faeces and the

Table 2 Percentage of N in the diet, the ratio of the weight of feed added to the weight of fish produced (FCR) and total N discharge from different farmed fish species (Gillibrand et al. 2002)

Species	Nitrogen in the diet (%)	FCR	Species factor	Total N discharged (kg/t fish produced)[a]
Salmon	7.2	1.17	1	48.2
Halibut	6.25	1.3	1.4	67.1
Turbot	9.3	1.3	1.8	86.9
Cod	9.3	1.1	1.5	72.3
Haddock	9.3	1.1	1.5	72.3

[a]Expressed as the relative rates of discharge of waste as ratios to that for salmon, thereby giving species-specific discharge factors for N

dispersal characteristics of the water body, based upon the fundamental approach initially described by Gowen et al. (1988). The recent main developments are recognition of the facts that fish faeces may not closely resemble coherent particles and that the resuspension of bottom sediments may be important in some locations, and the consequential redistribution of sedimented waste (Henderson et al. 2001).

Impacts of aquafeeds and feeding practices on the marine environment

The effects of feed inputs and feeding techniques from aquaculture on the marine environment in the form of nutrients and organic loadings can be classified according to the spatial scale of the impact. Thus, increased organic content and sediment particle size in relation to the benthos may lead to local oxygen depletion (ICES 2002). Nutrient release can have a large-scale impact, leading to eutrophication (and plankton response, or wild fish population response). The use of natural resources at a high level in the food chain and of fossil energy may have a global impact.

Use of fish meal

Fishmeal has historically been the most valuable protein source in formulated feeds for farmed carnivorous fish species. Salmon farming depends on fishmeal and/or fish oil supplies. Fishmeal is produced almost exclusively from small species of pelagic bony fish (living in the surface waters or middle depths of the sea) for which there is little or no demand for human consumption and, even if there were, it might be difficult and costly to get them to markets in suitable condition. Some larger pelagic fish species are, however, marketed for direct human consumption. Thus, the EU prohibits the landing of herring (*Clupea harengus*) with the objective of processing them into fishmeal (Bernal 1999).

White fishmeal, from demersal species, accounts for only 5% of total fishmeal production (Tacon 1995). The raw material for the commercial production of fishmeal generally relies on the waste from filleting operations, and it would be difficult to channel these by-products into direct human consumption (James 1995).

The production of fishmeal has remained generally stable over the past 10 years except for *El Niño* years (Barlow 2000). Over the last decade fishmeal production has been around 6–7 million tonnes annually and is likely to remain so over the next decade, provided that *El Niño* events (e.g. 1998–1999) do not cause dramatic changes (FAO 2002). Decadal scale non-random variability in the abundance of sardine and anchovy populations is thought to be regulated by large-scale changes in oceanographic and climatic conditions (James 1995). In an *El Niño* year, warm water currents are driven down the Pacific coast of Peru and Chile, changing primary production patterns and forcing fish deeper and further out into the ocean in search of food and a cooler environment. This causes a severe decline in the biomass and total production of small schooling pelagic fish and impacts on other coastal resources.

The main fishmeal-producing countries, in order of output (from first to ninth), are Peru, Chile, China, Thailand, Japan, USA, Denmark, Iceland and Norway (Table 3). In Peru, anchovy (*Engraulis ringens*) is by far the most important species for fishmeal production, followed by the Pacific sardine (*Sardinops sagax*). The Chilean fishmeal industry uses anchovy, sardine and jack mackerel. In Europe, fishmeal and fish oil are mainly derived from seven species (or species groups): sandeel (Ammodytidae) and capelin (*Mallotus villosus*), which are fully utilized and processed into fish meal; Norway pout (*Trisopterus esmarkii*) and blue whiting (*Micromesistius poutassou*), which are moderately to fully utilized and processed into fish meal; sprat (*Sprattus sprattus*), horse mackerel (*Trachurus trachurus*) and herring, which are moderately utilized (although, as noted above, in the case of herring, there are legal restrictions on its use) (Bernal 1999). UK total fishmeal consumption in 2001 was about 280,000 tonnes, of which 170,000 tonnes was imported (Table 3), (FIN 2003).

Aquaculture continues to expand rapidly worldwide and the usage of both fishmeal and oil is steadily increasing (FAO 2003). If the growing aquaculture industry is to sustain its contribution to world fish supplies, it must reduce wild fish inputs in feed (Pauly et al. 1998; Naylor et al. 2000). Whether supplies of wild fish will meet the demand and requirements for aquacultural use in the future depends on management practices and the conservation of stocks and on the relationships between fishmeal/fish oil producers, exporters and importers. However, the supply of fishmeal and fish oil from conventional sources is limited and cannot be significantly increased. The increased use of alternative marine protein sources, for example, krill,

Table 3 World fish meal production (tonnes) in 2001[a]

Countries	World fishmeal production in 2001 (tonnes)
Peru	1,833,000
Chile	704,000
China	670,000 (estimated at 2000 level)
Japan	390,000 (estimated at 2000 level)
Thailand	387,000
USA	353,000
Denmark	299,000
Iceland	268,000
Norway	256,000
Rest of the world	1,173,000 (estimated at 2000 level)
Total world	6,333,000
UK summary	UK fishmeal in 2001 (tonnes)
UK consumption	280,000
Imports from EU	60,000
Imports from non-EU	170,000
UK production	50,000

[a]International Fishmeal and Fish Oil Organisation (IFFO) and theUK fishmeal summary 2001; Fishmeal Information Network (FIN 2003)

is an option (see below), although there may be significant environmental costs associated to these sources. Given the projected increases for aquaculture in Europe and the rapid continuing growth and increased intensity of aquaculture worldwide, demand is likely to exceed supply unless the dependence on fishmeal and oil is significantly reduced (Tacon 2003). Fisheries for fishmeal/oil species need regulations which will keep them within safe biological limits and subject to management regimes designed to ensure that they remain within these limits (ecosystem approach to fisheries management (FAO 2003).

Markets for fishmeals and oils are affected not only by demands from aquaculture but also by demands from terrestrial livestock farms and the availability and prices of other proteins/oil such as soybean meals and oils, corn and wheat gluten meals, canola, among others (Starkey 2001). Chamberlin and Barlow (cited in Costa-Pierce 2002b) stated, in response to Naylor et al. (2000), that, owing to the primacy of market forces as opposed to fisheries management, ‘‘if fishmeal were completely eliminated from aquaculture feeds, it would continue to be produced for land animals’’ (Costa-Pierce 2002b). Tidwell and Allan (2001) argue that aquaculture has simply reallocated the fishmeal production and not increased the total amount of pelagic fish harvested for use in fishmeal. However, by comparing efficiencies of terrestrial and aquatic protein production systems, scientists, policy-makers and the public can address in a more rigorous manner the research, policy and regulatory needs for ecologically sustainable aquaculture (Costa-Pierce 2002a).

The argument that if aquaculture ceased or decreased its demand for fishmeal/fish oil, the species harvested for this purpose would become available for direct human consumption is relatively weak. Firstly, it is not clear if there is a market for direct consumption of species like Norway pout and sandeel. Secondly, there are other ways to increase fish availability for human consumption, including fish stock enhancement, utilization of the discards and reduction of processing wastage (New 1995).

Production efficiencies, in terms of edible mass, for aquaculture range from 2.5 to 4.5 kg dry feed/kg edible mass compared with 3.1 for broiler chickens, 10.2 for beef and 17.4 for lamb production systems (Costa-Pierce 2002b). Nevertheless, production efficiency in aquaculture will be higher for predators such as salmon than for herbivores such as catfish and carp.

Rapid advances in aquaculture research and the development towards sustainability and best management practices have reduced the amount of fishmeal that is required to produce 1 kg of salmon. For example, based on the FCR of 1.17 for salmon (Table 2), 1.17 kg of feed is required to produce 1 kg of salmon. At an inclusion level of 45%, 0.52 kg of fish meal will be used. Since about 5 kg of raw fish is required to make 1 kg of fish meal (De Silva and Anderson 1995), approximately 2.6 kg of raw fish is required to produce 1 kg of cultured salmon, and not the 3.16 kg of wild fish as estimated by Naylor et al. (2000), although our figure is within the range for salmonids (2.6–3.3) given by Tacon (2003). Other net fish consumers are marine eels (pelagic input per unit of production: 3.4–4.2 kg per kilogram fresh weight), marine shrimp (1.7–2.1) and freshwater crustaceans (1.0–1.3). Net fish producers in culture conditions include milkfish (0.33–0.42), catfish (0.28–0.35), tilapia (0.24–0.29) and carp (0.15–0.19) (Tacon 2003).

It would be a mistake to ignore the significance of fish oils. Fish oil contains high levels of Omega 3 highly unsaturated fatty acids (HUFA), widely known for being essential for a healthy human diet. There is a risk that quality fish oils could prove to be the more finite commodity in the next decade as aquaculture is projected to use 87% of the world's supply in 2010 (FAO 2002). This has obvious implications for the salmon sector and others where much of the dietary energy is provided as oil at present.

Inclusion rates of fishmeal in aquafeeds vary widely according to species cultured, life-cycle stage for which the feed is intended and composition of the fish meal available. The percentage of fishmeal inclusion in salmon feeds (carnivorous) is relatively high (35%–45%) compared with catfish (herbivorous) (2%) (Table 4). The share of fishmeal used in aquaculture varies from between 17–20% (Pike 1999) to around 35% (Chamberlain and Barlow 2000; Barlow 2002) (Fig. 4). The UK is the second largest salmon producer in Europe (after Norway). In 2002, UK fishmeal consumption was about 240,000 tonnes, of which 190,000 tonnes was imported and 50,000 tonnes was produced in the UK (Table 3). Approximately 60% of total UK fishmeal consumption was in the aquaculture sector, 28% in poultry, 10% in pigs and 2% in miscellaneous other sectors (FIN 2003). In the EU as a whole, fishmeal production in 2001 was 550,000 tonnes, and usage by sector was 50% in aquaculture, 20% in poultry, 20% in pig and 10% in other farmingsectors (FIN 2003). The European aquaculture industry currently relies to a significant extent upon fishmeal from other parts of the world, especially Central and South America.

As feed costs constitute roughly 40–50% of production costs in aquaculture, the use of plant proteins is increasingly becoming an economic necessity because such proteins are readily available, the quality is good, costs fluctuate less and production is more likely to be sustainable. Furthermore, the use of plant protein sources in

Table 4 Percentage of fishmeal inclusion in feeds produced for aquaculture (Barlow 2002)

Species	Percentage of fishmeal inclusion in feed produced	Percentage of fish oil inclusion in feed produced
Carp	4	0
Tilapia	7	1
Shrimp	25	2
Salmon	35	28
Marine fish	45–55	8–12
Trout	30	28
Catfish	2	1
Milkfish	12	2
Carnivorous freshwater fish	15	6
Eel	50	5

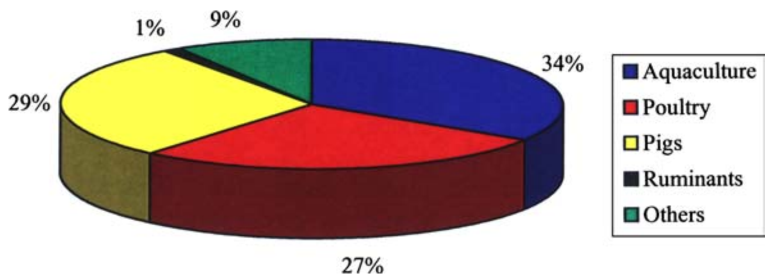

Fig. 4 Worldwide fishmeal use for 2002

aquaculture feeds reduces the reliance on fishmeal. Alternative protein sources to replace fishmeal (e.g. soya) and methods of reducing the discharge of feed from farms have been examined (Kaushik et al. 1995; Hardy 1996). However, higher levels of fishmeal substitution are currently constrained by ''anti-nutritional factors'' found in many plant protein meals, adverse effects on fish health and welfare and the higher cost of complex balanced formulations and additives (Francis et al. 2001). Beyond a certain point of replacement there will be an effect on product quality; for example, substantial reductions in fish oil will result in a reduction in Omega 3 HUFA in the product (Kaushik 2003).

Although carbohydrates can be used as an alternative to fishmeal, research has shown that certain fish, such as rainbow trout (*Oncorhynchus mykiss*), use dietary carbohydrates rather poorly: they show prolonged postprandial hyperglycaemia (Panserat and Kaushik 2002). The efficiency of glucose utilization as an energy source by rainbow trout is low (Panserat et al. 2000). Further research is needed to understand dietary carbohydrate utilization in fish in order to enable the development of diets that can replace fishmeal as the major source of dietary protein for farmed fish.

Krill represents a good resource of both marine protein and an oil that is highly enriched with carotenoids and Omega 3 HUFA. However, krill is a key species in the food web in Antarctic waters, and any major fishery would need a management regime that would take into full account of the ecosystem effects. Furthermore, krill is rich in fluorine, and current EU legislation relating to animal feeds would preclude its use. There are also technical difficulties both in catching (the fine mesh nets require tremendous power to move through the water) and preserving kill (the small animals begin to degrade very rapidly) (SEAfeeds 2003). Trimmings from the processing of human-grade fish are available, although this material is typically not oil-rich. The use of trimmings from aquaculture itself would contravene EU legislation designed to prevent ''loop feeding'' and associated health risks (SEAfeeds 2003). Further research on fish physiology and nutrition as a means to improving our understanding of the metabolic requirements of fish and research on feed ingredients and health management would help aquaculture to be sustainable (Tacon 2000; Stead and Laird 2002).

Nutrient discharge

From a long-term perspective, there are two aspects of nutrition that are critical for the sustainability of aquaculture: (1) the need for alternative protein sources and (2) the need to develop diets that reduce the inputs of N and P into the environment (Bernal 1999). Nutrients that can enrich the natural environment around marine farms are N, P, C and Si.

Nitrogen (N) and phosphorus (P)

Hall et al. (1992) estimated that between 67 and 80% of the N added to cage systems is lost to the environment, of which the majority (50–60% of total N) is lost in dissolved form either directly from the fish or by benthic flux from solid waste beneath the cages. Enell (1995) reported a reduction in loss from 132 to 55 kg N/tonne fish between 1974 and 1994 in the Baltic region. Recent research estimated that dissolved N released by a Scottish salmon farm is 35–45 kg N/tonne fish produced and that the total discharge of N is 45–48.2 kg N/tonne fish produced (Davies 2000; Fig. 3). Recently, a reduction in N released to the environment was achieved through a general reduction in FCR, which is currently 1:1 for salmon farming in Western Europe (Table 2; Pearson and Black 2001). Large European rivers are the main source of N loading (approximately 50%) and C input in coastal waters. Daily nutrient loads from rivers from Belgium, the Netherlands, Germany, Norway and Denmark entering the North Sea have been estimated (for 1997–1998, using the ERSEM model; Heath et al. 2002). Salmon farming contributed approximately 6% of total N input into the seas around Scotland and 13% of P, based on 2001 production figures (AQCESS 2000). However, in some areas of the west of Scotland with small catchment areas and low levels of human habitation, aquaculture inputs represent more than 80% of the total (Heath et al. 2002). Effects on water quality due to nutrient inputs from aquaculture have been studied in other European countries – for example, Finland – where nutrient enrichment from aquaculture has a local effect, and in Greece, where aquaculture represents a major source of nutrient input although the area maintains its oligotrophic characteristics (AQCESS 2000; Machias et al. 2004).

In the marine environment, losses of P from fish farms have been estimated as 19.6–22.4 kg/tonne fish (trout) produced, 34–41% of which is released in dissolved form with the remainder lost by sedimentation (Holby and Hall 1991). Holby and Hall (1991) estimated that 4–8% of the sedimentary P was returned to the water column per year. Scottish sea lochs may retain a substantial proportion of P inputs due to biogeochemical factors, and it may be that coastal waters become P depleted in summer as they pass through the sea lochs (Berry 1996).

The nutrient ratio (N:P)

Fish farming enriches the water column with dissolved organic and inorganic nutrients and causes a reduction in dissolved oxygen, both in the vicinity of the fish farm and at the site of remineralization of the waste products. Nutrients discharged from an external source into coastal waters can bring about changes in the ecology of phytoplankton, which is part of the eutrophication process (Gowen and Ezzi 1992). However, Gowen et al. (1988), who studied eutrophication resulting from hypernutrification, concluded that the local fish farm had not caused phosphate and nitrate hypernutrification in Loch Spelve, Scotland, and that there was no increase in primary production of phytoplankton. With the exception of a few locations, turbulent mixing may restrict the amount of light which phytoplankton receives. With the exception of a few loch sites, enrichment by fish farm nutrients is of minor importance in Scotland relative to natural levels. At its present (2002) level, fish farming in Scotland is thought to have a small effect on the amount and growth rate of Scottish coastal phytoplankton except in a few heavily loaded sea lochs (Scottish Executive 2002).

The nutrient ratio (N:P) of the organisms growing in sea water will influence – and be influenced by – the N:P ratio of the medium in which they grow (Berry 1996). Low dissolved inorganic N:P ratios (<8:1) could indicate that bacteria with an N:P ratio of approximately half that of photosynthetic phytoplankton dominate pelagic biological activity, whereas higher N:P ratios (>8) can indicate phytoplankton dominance (Berry 1996). The N:P ratios in the coastal waters of northwestern Scotland are generally highest in late winter/early spring, (averaging 48:1, based on data collected over a 30-year period) in contrast with an August low of 6.13:1 (Turrell and Slesser 1992; Berry 1996). In Loch Creran (west coast of Scotland), N:P ratios were found to vary between 8.3:1 and 6.4:1 in the winter and between 4.3:1 and 4:1 during the summer (Berry 1996). Ryther and Dunstan (1971) suggested that an N:P ratio of 10:1 was a reasonable value for the growth of photosynthetic phytoplankton. In a subsequent Scottish study, Gowen and Ezzi (1992) calculated the ratio of soluble N:P discharged from fish farms to be 10.5:1.

Carbon

Several studies have examined the total amount of C (feed and faeces) released to sediments from fish farms (Hall et al. 1990; Findly et al. 1995). Estimates of wastes have varied between 29 and 78% of input C, depending on the year (Pearson and Black 2001). A salmon farm with an annual production of 500 tonnes might use 750 tonnes of food in a year (1.5× annual production) with a C content of about 330 tonnes (Gillibrand et al. 1996). Thus, Gillibrand et al. (1996) concluded that the quantity of solid waste C from the farm, at 44% wastage released, is approximately 145 tonnes. Estimates of C inputs suggest that fish farm feed may contribute up to 50% of the total particulate organic C supply (Gillibrand et al. 1996). The recent use of more efficient feeding strategies, the greater palatability of the diets and the use of highly digestible pelleted diets have led to lower FCR and less waste (ICES 2002).

Silicon (Si)

There has been only one study of Si budgets in farmed salmonids (Holby and Hall 1994). Pearson and Black (2001) reported that almost all of the Si added in the aquafeeds in a trout farm was lost to the environment and that this accounted for 20% of the total Si budget. However, the same study reported that the farm itself provided a good habitat for organisms utilizing Si from sources external to the farm. It has been suggested that cage farms should be sited in areas that are well supplied with fresh seawater and that the addition of silica to feed formulations should be considered.

Toxic algal blooms

The perturbing effect of fish farm waste on nutrient element ratios can be shown to be generally small.Dilution is generally rapid at marine sites, and subsequent dispersion is immediate. Concerns continue to exist, however, regarding nutrient effects in relation to toxic algal blooms, although it is widely recognized that in many areas nutrient inputs from the agricultural land well exceed those from fish farming operations. Dissolved inorganic nutrients released from fish farms during the intensive cultivation of salmonids (principally salmon) represent one source of allochthonous nutrient input to coastal waters, and their release into what are considered to be unpolluted coastal waters of countries such as Canada, Ireland, Norway and Scotland has been viewed with concern by some Government and non-Governmental organisations (NCC 1990). The accumulation of algal biomass or the occurrence of algal blooms can be so great that it discolours the water and can favour flagellate species that are toxic to other forms of marine life (Shimizu 1989).

An ongoing debate has been the extent to which increased nutrient levels from fish farms have fuelled the occurrence of toxic algal blooms. Toxins are produced naturally by some species of phytoplankton (in conjunction with bacteria). The most common effects of toxins on humans are paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), diarrhetic shellfish poisoning (DSP) and neurotoxic shellfish poisoning (NSP).

In the oligotrophic Mediterranean, Pitta et al. (1999) found little effect on water quality and plankton communities near fish farming sites. However, it is not easy to identify causal links, especially as there are reports of harmful blooms that do not appear to be associated with pollution. There is also a possible link between climate change and an increase in harmful algal blooms (Davenport et al. 2003).

Effects on benthos (sediment)

The main factors controlling the level of enrichment of the benthos and water column in the vicinity of a salmon farm – and the rate of recovery – are the size of the farm, husbandry methods and hydrography of the site. Studies on benthic impacts of cage aquaculture (Costa-Pierce 2002b) have shown that effects are localized and reversible by fallowing (Table 5). In Scottish West Coast waters, the main effect of benthic enrichment does not extend in excess of a distance of 50 m from the cages of the farm. Brown et al. (1987) reported that there were four zones of effects on the benthic profile from intensive cage culture: (1) an azoic zone immediately under the cages; (2) a highly-enriched zone 0–8 m from the cage edge, with a high biomass dominated by a large number of a few opportunistic species; (3) a slightly enriched transitional zone between 8 and 25 m from the cages; (4) a normal zone beyond that. The distances associated with all of these zones may vary depending on local hydrography, and some effects on the benthos may be measurable at distances greater than 25 m from the cages (Pearson and Black 2001).

Areas located 1000 m from the cage have been shown to represent normal conditions of sediment profiles as compared with samples taken beside a fish cage and from samples 25 m from the fish cage (Gowen et al. 1988; Pearson and Black 2001). The sea bed directly beneath a fish cage has been found to show symptoms of chronic pollution due to the sustained high level of input of organic material (Pearson and Black 2001). Results of a study by Henderson et al. (1997) showed that waste material from marine fish cages influences the lipid composition of sediments underlying the cages. While fallowing changes the sediment chemistry and macrofauna within 3 months, it takes 21–24 months for the situation to revert to previous unpolluted standards (normal community) (Pearson and Black 2001).

Cage farms make a significant contribution to the production of surrounding native populations (fish and infaunal benthos), and Pearson et al. (1995) suggested that the production of infaunal benthos (animals living within the sediments) close to the cages in the West of Scotland is four- to sixfold higher than the background levels. However, diversity has been found to drop, and polluted marine sediments are dominated by a very few opportunistic macrofaunal species, such as *Capitella* sp., often at high abundances. There has been evidence that seagrass meadows in the Mediterranean have been severely affected or become totally eliminated as a

Table 5 Studies on impact on finfish aquaculture on the benthos

Doyle et al. (1984)	Effects extending 20–45 m from the culture
Brown et al. (1987)	Effects extend up to 15 m away from the cages. Transitional zone occurred at <25 m and a clean zone at distances >25 m
Gowen et al. (1988)	at distances between 30 and 40 m away from cages there is a change in species composition
Lumb (1989)	Within 50 m of the edge of the cage there is an impact dependent on seabed type
Ritz et al. (1989)	The macrofaunal community structure indicated a moderately disturbed condition under a normal feeding. However, it has adopted an undisturbed condition 7 weeks post-harvest of farm stock. No such a change occurred under a cage which contained fish continuously over the same period.
Weston (1990)	Effects were evident at least 45 m from the cages and more subtle effects at least 150 m distant
Kupka-Hansen et al. (1991)	Increase in the sedimentation rate of organic waste under a fish farm
Tsutsumi et al. (1991) and Tsutsumi (1995)	Changes in benthic fauna and the reduction in the abundance of the benthic communities by a local fish farm. Increase C flux to the benthos
Holmer and Kristensen (1992)	Sediment metabolism beneath the net cages was about tenfold higher during farming period than the control site 30 m away
Hall et al. (1992)	The sediment below the cages was very rich in N
Wildish et al. (1993)	Ammonia concentrations were increased slightly as a result of input from fish farms but not to levels that are toxic to salmonids. Accumulation of particulate wastes under the cages
Hargrave et al. (1993)	Benthic fluxes of ammonia and oxygen uptake were four- and 27-fold higher directly beneath cages
Johannessen et al. (1994)	No influence of fish farming could be detected 250 m away from cages
Krost et al. (1994)	Affected area extended the margins of the fish farm by 3–5 m. Sediment under the farm is anoxic, no benthic macrofauna
Wu et al. (1994)	Impacted area did not extend beyond a distance of 1–1.5 km
Wu (1995)	Field studies showed high pollution from fish farms due to feeding unpelleted, ground-up trash fish within 1 km of cages
Pearson et al. (1995)	Production of infaunal benthos close to the cages is four- to sixfold the background levels
Findlay et al. (1995)	Effects are spatially limited. Little or no C flux 10 m from the cages. Seasonal trends and storm-related resuspension events also significantly affected the sediment communities
Koussouris et al. (1995)	Impact of fish farming in coastal environment is the accumulation of organic material on the sea bottom and within a range of 25–50 m around the cages
Beveridge (1996)	Deprivation of benthic fauna in the vicinity of fish cages
Davies et al. (1996)	Amount of cell division underneath the cages
Henderson et al. (1997)	Waste material from the cages influences the lipid composition of sediments underneath the cages
Hargrave et al. (1997)	Benthic enrichment beneath the cages
Karakassis et al. (1999)	Increases in benthic diatom biomass beneath cages

Table 5 continued

McCaig et al. (1999)	Disruption of N cycling in the sediments beneath the cages
Karakassis et al. (2000)	Impacts of fish farming on benthos in the Mediterranean vary considerable depending on site characteristics
Morrisey et al. (2000)	Impact of marine farms on the benthic environment (to the seabed below a salmon farm) is a reversible process
McGhie et al. (2000)	Accumulation of organic matter was confined to an area directly underneath the fish cages. Thirty metres from the centre of the cage indicators of fish cage waste were still elevated compared to 1.1 and 1.4 km. A 12-month fallowing period was sufficient to return the site to pre-farm oxic conditions
Dominquez et al. (2001)	Average N content of the sediments underneath the cages was higher than 60 m and 200 m from the cages. No significant physical and chemical characteristics of sediments due to the fish farm operation because of the small size of the farm, the first year of operation and the high average velocity of water currents (6 cm/s)
Heilskov and Homer (2001)	Oxygen flux rates are higher beneath a fish farm in Horsend Fjord
Chamberlain et al. (2001)	Effects up to a 40 m around the mussel farm. Biodeposits are influences by local currents
Pearson and Black (2001)	Moderately enriched conditions at 25 m from the cage and beside the cages negative impacts
Karakassis et al. (2002)	The impacted zone was restricted to under the cages and a small distance of a few metres beyond
Brooks et al. (2003)	Effects extended to at least 50 m from the net-pen's perimeter
Nickell et al. (2003)	High oxygen uptake rates and oxygen fluxes in sediment beneath fish farms

consequence of fish farming (Delgado et al. 1999). Nevertheless, fish farming in the Mediterranean region has induced less severe impacts than those caused by other types of organic enrichment (sewage, oil platforms, paper processing etc), where the heavy organic loading of sediments results in azoic zones where worms, bivalves or crustaceans can not survive (Karakassis et al. 2000). In Greece, the macrofaunal community was found to be affected by organic wastes at a distance of up to 25 m from the edge of the cages. Underwater video surveys beneath fish farms in the western and eastern Mediterranean areas showed that fish of various species aggregated under the fish cages during feeding (Karakassis et al. 2003; Smith et al. 2003) and, as noted above, there may be a beneficial effect on local fisheries (Machias et al. 2004).

Conclusions

Bubridge and Burbridge (1994) identify three ways in which it would be possible to achieve control of feed impacts from aquaculture: (1) control of the sites where the culture farms are located; (2) control of the released effluents; (3) monitoring of impacts generated by effluents once the farm begins its work. Polyculture, or integrated aquaculture associating shellfish and algae culture with fish culture may be part of the solution (Cheshuk et al. 2003). The development and application of Environmental Quality Standards (EQS) and the design of models for evaluating environmental impacts are other initiatives for controlling and monitoring the environmental impact of fish farms (SEPA 1998).

Dosdat (2001) summarized improvements in fish nutrition during the last 10 years. FCR has been improved, since it has decreased from 2:1 to 1:1.1 in this period (in salmon culture), although there is a limit (imposed by the physiology of the organisms). There has also been genetic selection and improvement in the cultured fish (its basis is the genetic variation of a single species, and selection within that variability to promote better characters) for feed efficiency (ICES 2002). Actual digestibility of organic matter, protein and P in feedstuffs (e.g., pre-cooked starch, low temperature fishmeal) has been analysed, and the energy to protein ratio of feeds has been evaluated. The level of protein and amino acid balance has been determined (decreased N content in the feed, 45% protein in the feeds), and the P content in the feeds has been decreased (from 1.5 to 0.7 in salmon feeds).

One of the limits of aquaculture expansion is likely to be the availability of feeds derived from fish meal/fish oil resources. Concerns about contamination and possible risk to humans (e.g. related to level of dioxins in fish) have been expressed. Although progress has been made with respect to the partial replacement of fishmeal by a number of alternative (e.g. plant-based) ingredients, completely fishmeal-free diets are still not available, and this is an issue for continuing research. Future research aimed at gaining an understanding of the physiological basis of observed growth in terms of anabolic and catabolic processes will enable informed decisions to be made on the modification of diets and feeding regimes. In addition, metabolic indicators used may prove useful indices of short-term growth rate when assessing potential diets. Research is still needed to improve feed quality and usage in aquaculture, which will result in better growth and survival of farmed fish. Feeds should be designed to offer high digestibility, low rates of N excretion and less dietary protein to minimize nutrient discharges from aquaculture to the environment and ensure the sustainability of the aquaculture.

The role of nutrition in the quality of market-sized farmed fish and the long-term benefits of the aquaculture industry and the environment should continue to be thoroughly researched.

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