Sustainable development of marine aquaculture off-the-coast and offshore – a review of environmental and ecosystem issues and future needs in temperate zones

Marianne Holmer
Institute of Biology, University of Southern Denmark
Odense, Denmark
E-mail: holmer@biology.sdu.dk

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ABSTRACT

Aquaculture is predicted to move offshore in the near future and this review addresses the interactions between aquaculture and the environment under offshore conditions. Most environmental impacts are predicted to decline, as the dispersion of waste products is increased under offshore conditions due to larger water depths and stronger currents and winds. The benthic communities may, however, be more sensitive to organic loading, as deep sea fauna is adapted to low organic matter inputs. The attraction of wild fish and interactions with fisheries may be the same as at near shore farms, whereas the carbon footprint increases due to higher energy use for transportation and the risk of escapees increases in the larger farms placed under rough weather conditions. Some major gaps of knowledge in predicting environmental impacts under offshore conditions are the lack of knowledge on the deep sea communities and in particular on habitats sensitive to organic matter inputs. Experimental evidence of organic matter enrichment is needed to understand the assimilative capacity of deep sea sediments, as well as the response of the infauna to organic loading. Also knowledge on cultured and wild fish with respect to genetic, disease and parasitic interactions need further examination before farming offshore can be recommended.

CHARACTERISTICS OF OFF-THE-COAST AND OFFSHORE AQUACULTURE IN TEMPERATE ZONES

Introduction

Based on the high expectations for development of aquaculture, offshore mariculture has received considerable attention over the last decade. While present marine aquaculture production mainly takes place in nearshore farms there is a successive move towards offshore sites. Pushed by the overall highly competitive use of coastal seas, the scarcity for available space has increased. In addition, the existence of good water qualities in the open ocean such as oxygen conditions, less pollution, less eutrophication, has acted as "pull" factor for offshore developments. The motivations for movement include environmental aspects of intensive cultivation of particular fish in cages, and compared to coastal farming, offshore locations are more exposed increasing the dispersal of both dissolved and particulate waste products. The development within offshore production during the last decade has, however, focused on finding technology solutions and suitable sites, whereas less focus has been on the environmental issues of offshore production. The technological development seems now to be in such an advanced stage, that offshore production is going to take place. There are regular reports in the media on expansion of offshore production, even in these years despite major constrains, such as the financial crisis and the major losses encountered for salmon production in Chile and cod production in Norway, due to disease and declining prices, respectively. As an example, Marine Harvest just announced plans for investing £40 million in four farms in Scotland, which all together will produce 20 000 tonnes of salmon. GreatBay Aquaculture in the United States of America is planning a farm consisting of single cages hosting up to 25 000 whitefish located 3–20 miles offshore, and New Zealand is planning a 2 695 hectare of mussel farms, which will generate 200 jobs. The prospects for offshore development are thus quite optimistic.

Scientific publications on environmental issues at offshore farms, as defined in this review (Table 1), are not available. The few published studies are from test sites with low fish production or report ideas on possible environmental constrains. Much more peer-reviewed information is available for "off-the-coast" farming, although it can be difficult to find this information, as only few publications distinguish between coastal and off-the-coast farming. At present up to half of salmon production in Norway can be characterized as "off-the-coast", but the Norwegians consistently refer to coastal aquaculture production. Documented evidence of environmental effects are thus limited for offshore farming (<10 farms in temperate waters) and from off-the-coast farms difficult to find, and this review will therefore use both results available from existing farms, and include more theoretical considerations of possible environmental effects of aquaculture in particular for offshore farms. The review is further constrained by the significant gaps in scientific knowledge from particularly deep sea habitats. For instance, little is known about the dispersal of many deep-sea organisms, which may have clear consequences for the impacts on sediments and for prediction of the success of fallowing practices. Mapping coverage of sensitive habitats in the deep sea is also low, with the majority of effort targeted towards areas containing clearly identifiable habitats such as cold-water coral reefs (e.g. Roberts and Hirshfield, 2004). Current distribution data of mobile species such as deep-sea fish are poor, with many migration routes and aggregation areas currently unknown (Haedrich, Merrett and O'Dea, 2001). Without sound scientific knowledge, detailed species distributional and abundance data and physical habitat mapping, it is difficult to predict impacts of aquaculture activities in offshore zones. Such research gaps will be addressed in the dedicated section in the end of this review.

Definition of off-the-coast and offshore

According to the definitions given for off-the-coast and offshore production by FAO (Table 1), off-the-coast production differs from coastal aquaculture primarily by the distance to the coast and the degree of exposure (Table 1). Off-the-coast takes place in a zone from 500 m and up to 3 km from shore in water depths between 10 and 50 m. The sites can be protected, but currents are stronger, and wind and wave effects more severe compared to fish production closer to shore. Offshore production is located 2 km or

TABLE 1
Definitions for coastal, off-the-coast and offshore aquaculture based on some environment and hydrographic characteristics. Present study will not involve directly "coastal aquaculture"

	Coastal	Off-the-coast	Offshore
Location/ hydrography	< than 500 m from the coast ≤10 m depth at low tide; within sight usually sheltered	500 m–3 km, 10 m < depth at low tide ≤50 m; often within sight somewhat sheltered	2+ km, generally within continental shelf zones, possibly open-ocean >50 m depth
Environment	Hs usually <1 m, short period winds, localized coastal currents, possibly strong tidal streams	Hs ≤3–4 m localized coastal currents, some tidal streams	Hs 5 m or more, regularly 2–3 m, oceanic swells, variable wind periods, possibly less localized current effect
Access	100% accessible landing possible at all times	>90% accessible on at least once daily basis, landing usually possible	Usually >80% accessible, landing may be possible, periodic, e.g. every 3–10 days
Operation	Regular, manual involvement, feeding, monitoring, etc.	Some automated operations, e.g. feeding, monitoring	Remote operations, automated feeding, distance monitoring, system function

Terminology: Hs = significant wave height – a standard oceanographic term, approximately equal to the average of the highest one-third of the waves.

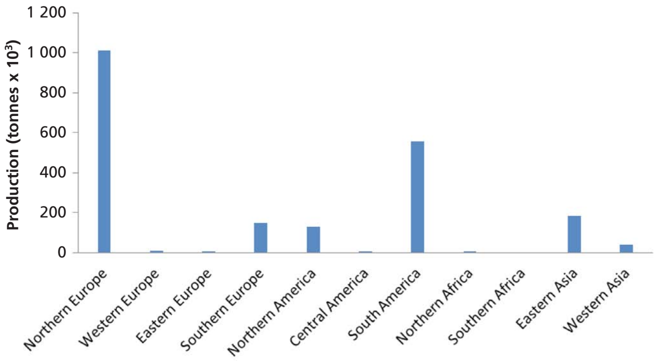
more from the shore in water depths >50 m with influence of ocean swells, strong winds and ocean currents. Annual fish production in the off-the-coast and offshore cage cultures is expected to be >1 000 tonnes, and perhaps up to 10 000 tonnes of fish. The production principles are, however, the same as for coastal production, i.e. fish will by cultured in net cages, dry feed pellets will be the main food source and the fish species already being cultivated will also be the main cultivated species in off-the-coast and offshore, but with use of more sophisticated and remote controlled feeding and monitoring systems. Also shellfish and algae cultivation has been proposed for off-the-coast and offshore production with principles similar to coastal aquaculture.

Current off-the-coast and offshore activities in the temperate zone

Due to the high cost and high technical skills required for offshore production, it can be expected that major aquaculture producing countries are the first to expand to offshore sites, in particular because the move is stimulated by the existing pressures on coastal zones, which is largest in countries with a high production. Most of the current temperate fish production in marine aquaculture is located in Northern Europe (40 percent), followed by South America (27 percent) with two dominating countries (Norway and Chile), whereas the production is rather equally distributed between a range of countries in other temperate zones (Figure 1, Table 2). Salmon is the dominant fish in aquaculture, with Norway as the largest producer followed by Chile until 2007, although this scenario will be likely different in 2008–2009 due to disease and collapse of the Atlantic salmon industry in Chile (see Alvial this volume). Production of salmon is around 10 times higher than seabream/seabass, which are the second largest fish species in aquaculture. China has the highest production of seabream/bass, followed by the Mediterranean Sea, with Greece as the largest producer. For shellfish, the Republic of Korea and Japan have very high production, while Spain also has a high output, approximately twice as high as the following countries: France, Chile and the United States of America. It is mainly these three groups of organisms (salmon, seabream/seabass and shellfish), which are projected for offshore production, but also other species such as cod, tuna, white fish and seaweeds are considered for offshore production (Buck and Buchholz, 2005; Troell *et al.*, 2009). All species are grown already under off-the-coast conditions.

Norway does not define their aquaculture production as off-the-coast or offshore, but use the term "coastal production". The trend over the past ten years has nonetheless been moving the farms to still greater water depth and still farther out into the outer parts of fjords and out from the coasts. It is estimated that about 50 percent of production

FIGURE 1
Temperate production of salmon, seabream/seabass by regions in 2007



Sources: Global dataset of aquaculture production (quantity and value) 1950-2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

can be defined as off-the-coast (for all parameters) and some of these even offshore (in terms of depth, but not by environment and access according to Table 1). In Spain, some of the fish farms are defined as off-the-coast/offshore. These are typically located several kilometers from shore in water depths <50 m with a wave intensity Hs <3–4 m, and are thus contained in the off-the-coast category. It is likely that some fish farms in the Mediterranean Sea are located at similar off-the-coast locations as in Spain, and tuna are typically farmed on off-the-coast locations. Also in the Faroe Islands, Chile and Canada, salmon are farmed in deep waters, but farms are often protected by their extensive archipelago and fjord systems. In a New Hampshire (USA) test site, experiments have been going on for several years using offshore technologies although at relatively low fish production. These studies include environmental monitoring of water quality, sediment and benthic fauna. Fish farming occurs at several off coast locations in the tropics (e.g. Caribbean), and since there is limited data available, only few of these cases will be included in this review. The areas considered suitable for offshore farming by depth ranges within EEZ's are shown in Figure 2.

TABLE 2
Top 10 countries in the production of salmon, seabream/seabass and shellfish in 2007

Salmon and rainbow trout (mt)		Seabream/seabass (mt)		Shellfish (mt)	
Norway	813 746	China	100 574	Republic of Korea	536 863
Chile	553 956	Greece	84 423	Japan	451 700
Canada	117 306	Japan	67 000	Spain	214 701
United Kingdom	132 457	Turkey	33 500	France	180 070
Faroe Islands	29 954	Spain	25 828	Chile	171 317
Australia[1]	20 000	Italy	14 351	United States of America	159 225
United States of America	11 001	Korea	12 415	New Zealand	102 508
Ireland	10 430	France	4 840	Netherlands	101 556
Denmark	6 882	Croatia	3 950	Ireland	45 866
France	1 168	Portugal	3 321	Canada	38 864
Total	**1 696 900**		**350 202**		**2 002 670**

[1] Estimated – data not available in FAO FishStat

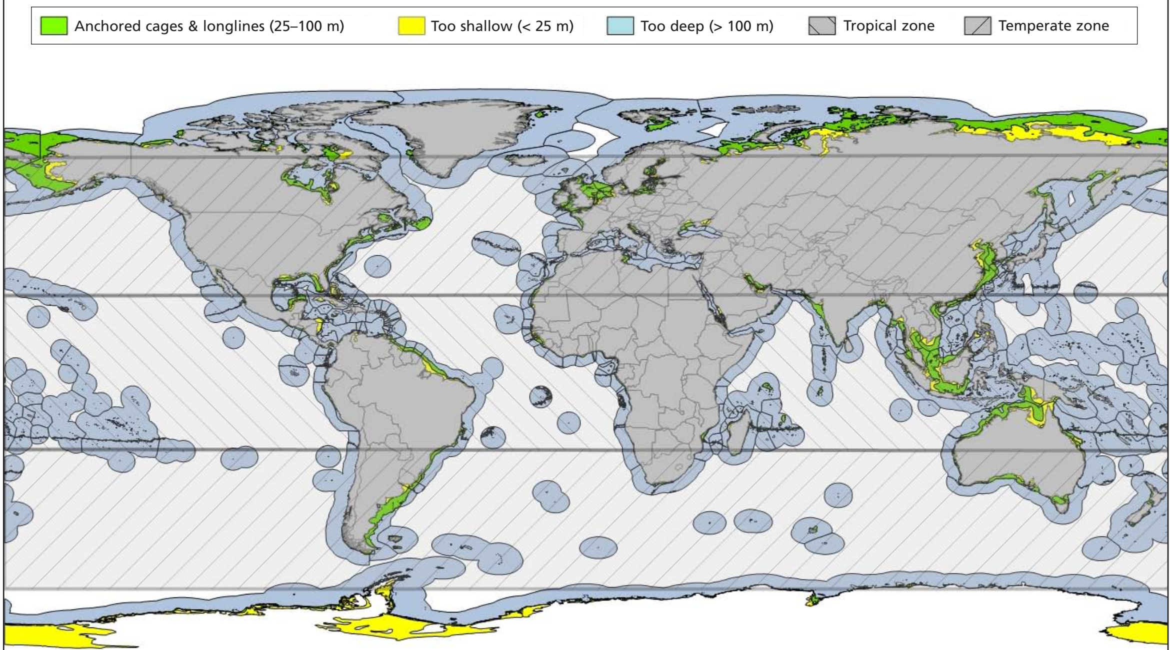
Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

ENVIRONMENTAL INTERACTIONS OF OFF-THE-COAST AND OFFSHORE PRODUCTION

Off-the-coast and offshore sites are characterized by greater depth and greater exposure compared with coastal sites. This means that the dispersion of waste products as the starting point is higher, partly due to stronger currents and wind effects and partly due to the greater water depth. It is, however, important to stress that hydrodynamics and bottom configuration can play an important role also in more exposed areas. In addition, the water column may be stratified due to temperature or salinity, affecting the sedimentation regime of waste products. Local variations in currents due to bottom topography (sills, basins) may also affect the dispersal of waste products. At present available data on offshore currents and hydrodynamics are limited, in particular at local scales, beyond ocean models. This is further constrained by the difficulty to obtain

FIGURE 2
Potential locations for offshore farming under temperate and tropical conditions

Potential for open ocean aquaculture by depth ranges within EEZs



Source: Kapetsky, Aguilar-Manjarrez and Jenness, 2013.

information due to high costs of ship operation and expensive equipment, and hamper the planning and siting of aquaculture activities in off-the-coast and offshore locations. Furthermore, it is important to consider the predicted size of the farms, which is often larger with typically 1–2 times higher annual productions (2–3 000 tonnes) compared to coastal production, increasing the discharge of waste products from each farm substantially.

Water quality at offshore and off-the-coast locations is possibly different from the coastal zones, displaying lower concentrations of nutrients and lower biological productivity. However, some off-the-coast and offshore locations are potentially very productive such as the North Sea and limited by seasonal variation in light rather than nutrients. This could play a role for the fate of dissolved nutrients from farms. Other water quality parameters, such as concentrations of toxins, chemicals and pollutants in general are expected to be lower at off-the-coast and offshore locations and thus beneficial for farm production, whereas the release of such compounds from farms may have greater impact due to higher sensitivity of these pristine environments.

The sedimentation of waste products from off-the-coast and offshore aquaculture production, and thus the input to the benthic compartment, will depend on a range of different factors, including source of sedimentation (feed pellets, composition of feed pellets, faeces, fish species, etc.), means of transport and rate of supply. The sediment conditions in deep locations could be coarser-grained and more advective sediments compared to coastal sites, propagated by the flow regimes in exposed areas. The sediments at advective sites would consist of shell sands or coarse grained carbonate sediments. Most deep sea sediments are, however, fine grained as a consequence of (low) sedimentation of fine particles and deposition of coarser material near the coast. One important aspect of the deeper sites is permanent low water temperatures and less light, which reduces the overall biological activity. Deep sediments can, to some extent, be considered less productive and carbon-starved with a lower fauna biomass and diversity compared to coastal zones, although there are areas of high productivity such as in vent areas and upwelling zones. Potential off-the-coast and offshore sites may also host a variety of sensitive habitats, such as cold-water corals and sponges.

Two of the most important factors distinguishing deep from shallow areas are lack of light penetration to the seafloor and the limited distribution of hard substrate with its associated flora and fauna. Presence of light controlled sensitive habitats such as seagrass meadows, algae on reefs, and other benthic vegetation is less in deep locations, and as these are particularly sensitive to fish farm waste products, movement to deeper locations is an environmental benefit (Holmer, Perez and Duarte, 2003). Light may, however, still play important roles in off-the-coast locations, in particular in the Mediterranean Sea with deep light penetration. Hard substrates are associated with the coast and thus most abundant closer to shores, but are also present in areas with strong bottom currents. In the last case, rapid dispersal probably limits the sedimentation of waste products.

Finally, impacts related to disease and escapees have similarities to coastal production, but also differences due to the location farther from shore, and will be addressed below.

Water quality

Due to a rapid dilution of nutrients from marine aquaculture, it is difficult to detect elevated nutrient concentrations around fish farms by direct measures, but use of bio-assays have shown increased nutrient availability for several hundred meters away from coastal cages (Dalsgaard and Krause-Jensen, 2006). Also by the use of a modified bio-assay approach, it was found that under oligotrophic conditions nutrients are transferred rapidly up the food chain, where they are available as food for higher organisms (Pitta *et al.*, 2009). Due to even higher dispersion at off-the-coast and offshore farms compared to coastal aquaculture, the use of bio-assays will be useful to measure the nutrient release at these locations.

Depending on location, pelagic primary production in off-the-coast and offshore waterbodies can be limited by nitrogen (often the case in the Atlantic) or by phosphate (in the Mediterranean) or light (in high latitudes). A combination of all three factors may also be the case, e.g. over a seasonal cycle. Coastal areas are generally limited by phosphate due to high nitrogen load from watersheds, but often with seasonal variations in nutrient limitation, and both nutrients may be limiting in the summer period (Conley *et al.*, 2009). Phosphate limitation is shifted to nitrogen limitation in open waters, and by placing fish farms at off-the-coast or offshore locations, nutrient release may have quite different impacts compared to coastal conditions. As there is a high release of nitrogen from fish farms in the form of ammonium, this may enhance the primary production in farm vicinities in open waters, although in the Mediterranean Sea nitrogen stimulation would depend on the availability of phosphate. Phosphate is, however, also an important waste product from fish farms, mostly in particulate form, and enhanced mineralization in the deeper water columns could regenerate phosphate for uptake by phytoplankton.

Impacts of nutrient enrichment on pelagic primary production in open waters have to some extent been studied experimentally, and some of the results are of interest for fish farming in off-the-coast and offshore locations. Probably the most widely known experiments are those in Antarctic, where fertilization of the water column with iron has been done, as iron is considered the limiting nutrient in these relatively nutrient (N, P) rich locations. A general observation from nutrient addition (N, P and Si) studies in temperate waters is a response of the lower trophic levels with increase in primary production (McAndrew *et al.*, 2007). The composition of the phytoplankton community change from small (<2 µm) to large species (>10 µm), and is often dominated by diatoms (McAndrew *et al.*, 2007). When dissolved organic matter is added experimentally to the water column as well, the microbial food web is also stimulated, in particular, if nutrients are added at the same time (Havskum *et al.*, 2003). Such a scenario is likely for fish farms, as dissolved organic matter leaks from wasted feed pellets and faeces along with the dissolved inorganic nutrients released directly from the fish or faeces, and are consistent with findings by Navarro, Leakey and Black (2008). They measured enhanced bacterial activity in the vicinity of a fish farm in a Scottish Loch with somewhat restricted water flow. Higher dispersion at off-the-coast and offshore locations may limit the activity, but it is possible that fish farming in off-the-coast and offshore locations will stimulate both bacterial activity and phytoplankton growth, with potential transfer to higher trophic levels through an efficient grazer food web (Pitta *et al.*, 2009). The pelagic productivity at higher latitudes will most likely show large seasonal variation, controlled by light and nutrient availability (Dandonneau *et al.*, 2004), and linked to farm production through nutrient release, as well as seasonal variation in grazing intensity. In the Mediterranean the seasonality may be less, as the productivity to a larger extent is controlled by nutrient availability, but light conditions, seasonal variation in temperature and farm production has to be considered as well (Psarra, Tselepides and Ignatiades, 2000).

Observed impacts on water quality

The few studies examining water quality and primary productivity near off-the-coast and offshore farms show no measurable change in nutrient concentrations (Table 3), but techniques like bio-assays, which are able to capture nutrients released from the farms into biomass growth, have not been applied yet. Using bio-assays at off-the-coast locations in the Mediterranean showed enhanced nutrient availability up to 150 m

TABLE 3
Overview of documented environmental impacts of temperate off-the-coast (OFC) and offshore (OFS) finfish and shellfish cultures divided into water quality, impacts on sediments and on the benthic fauna

Study	Type	Location	Water quality	Sediment	Fauna	Comment	Reference
Seabream/ seabass	OFS	East Mediterranean	No impact	No data	No data	–	(Basaran, Aksu and Egemen, 2007)
Seabream	OFS	Canaries	No data	Enhanced ON pools under cages	–	Low production	(Dominguez *et al.*, 2001)
Shellfish/ flounder	OFS	USA	No impact	No impact	No impact	Low production	(Grizzle *et al.*, 2003)
Atlantic tuna	OFC	West Mediterranean	No data	Enhanced OM pools and bacterial activity, reduced sediments	Disturbed community	–	(Vezzulli *et al.*, 2008)
Atlantic tuna	OFC	Adriatic	No impact	Enhanced P pools	No data	–	(Matijevic, Kuspilic and Baric, 2006)
Cobia	OFC	Puerto Rico	No data	Enhanced ON pools under cages	No data	–	(Rapp *et al.*, 2007)
Salmon	OFC	Norway	No data	Increased sedimentation, increased P content	See below	230 m water depth. Waste signals in bottom traps up to 900 m away	(Kutti, Ervik and Hasen, 2007)
Salmon	OFC	Norway	No data	Reduced sediments <250 m, no change in OM pools except P	Increased production, abundance, biomass, reduction in diversity	230 m water depth	(Kutti, Ervik and Hoisaeter, 2008; Kutti *et al.*, 2007)
Salmon	OFC	Chile	No impact	Enhanced OM pools	Decreased species richness	15–94 m water depth	(Soto and Norambuena, 2004)
Seabream/ seabass	OFC	West Mediterranean	No impact	Enhanced OM pools under cages	Reduced species richness and abundance	Impact at 2 out of 5 farms	(Maldonado *et al.*, 2005)
Seabream/ meagre	OFC	West Mediterranean	No data	Enhanced OM pools under cages	Disturbed community		Tomasetti *et al.*, 2009

TABLE 3 (CONTINUED)

Study	Type	Location	Water quality	Sediment	Fauna	Comment	Reference
Seabream/ meagre	OFC	West Mediterranean	No data	Enhanced OM pools under cages and downstream	Reduced species richness and abundance	–	(Aguado-Gimenez *et al.*, 2007)
Seabream/ seabass	OFC	Mediterranean	No data	Enhanced P pools	Abundance shifts	Seagrass impacted	(Apostolaki *et al.*, 2007)
Seabream/ seabass	OFC	Mediterranean	Nutrient availability enhanced up to 150 m	–	–	MedVeg project	(Dalsgaard and Krause-Jensen, 2006)
Seabream/ seabass	OFC	East Mediterranean	Transfer to higher trophic levels	No data	No data	–	(Pitta *et al.*, 2009)
Seabream/ seabass	OFC	Mediterranean	–	–	Enhanced seagrass mortality	MedVeg project	(Diaz-Almela *et al.*, 2008)
Seabream/ seabass	OFC	Mediterranean	–	Enhanced OM pools and bacterial activity, reduced sediments	–	MedVeg project	(Holmer and Frederiksen 2007; Holmer *et al.*, 2007)
Tuna	OFC	Spain	No data	No change in OM pools	Disturbed community up to 220 m away	–	(Vita *et al.*, 2004a)
Blue mussels	Coastal	Canada	No data	Enhanced OM pools and reduced sediments	–	–	(Cranford, Hargrave and Doucette, 2009)

ON: organic nitrogen; OM: organic matter; P: phosphorus.

(Dalsgaard and Krause-Jensen, 2006). A study in oligotrophic eastern Mediterranean at a off-the-coast site showed rapid transfer of nutrients to higher tropic levels (Pitta *et al.*, 2009), and a study of fisheries in the same area showed positive correlation between aquaculture production and landings, suggesting a transfer of wasted nutrients to higher trophic levels (Machias *et al.*, 2005). At the New Hampshire test site various water quality parameters have been measured over time, such as total suspended matter in the water column and dissolved oxygen (Ward, 2001). The New Hampshire test site is a research offshore farm financed by the University of New Hampshire, USA. It is located ten km from shore at 55 m of water, and has a varying production of fish (haddock, turbot) in up to four submerged cages. Each cage has a diameter of 25 m with a lower production of fish compared to commercial-scale, but it has not been possible to find production numbers for the different years investigated. Neither the total suspended matter nor chlorophyll-a concentrations showed major variation between farm and upstream and downstream stations. There were seasonal trends in concentrations and organic contents in response to phytoplankton blooms or storm events, but all values observed were within expected ranges for the various depths, seasons and locations on the inner shelf of New Hampshire. Based on these results, no evidence of the aquaculture production affecting these water quality parameters was observed. The dissolved oxygen saturation values were typically 100 percent or greater (saturated or supersaturated) near the surface and then decreased with depth at all stations independent from the location of the farm. The lower percentage saturation near the bottom was attributed to cooling of the water column and the annual variations in dissolved oxygen concentrations that occur in this region of the Gulf of Maine. The study concluded that no changes in the dissolved oxygen concentrations could be attributed to the aquaculture activities.

Bottom habitats

Enrichment of the benthic environments as a result of fast sinking particulate waste products from farms is considered one of the most significant impacts of marine aquaculture (Hargrave, Holmer and Newcombe, 2008). Under offshore and off-the-coast conditions, waste products are believed to be dispersed over larger areas, but due to the fast sinking rates of feed pellets and faeces (Cromey, Nickell, and Black, 2002; Magill, Thetmeyer and Cromey, 2006), sedimentation can be expected in the immediate vicinity of the farms (hundreds of meters). As deep sediments generally are considered carbon limited (Carney, 2005), inputs of waste particles are increasing the supply of a limiting factor in these relatively low organic content environments, and thus, potentially stimulating productivity of benthic fauna in the sediments. Carbon starved benthic fauna typically respond to organic enrichment with increasing total community density and wet weight (biomass) as a result of increased energy flow through the community, whereas the diversity is reduced (Gallucci *et al.*, 2008; Nilsson and Rosenberg, 2003; Pearson and Rosenberg, 1978). Hence, if organic waste deposition from excess feed pellets and faeces are affecting the benthos, a pattern of increased densities and biomass is to be expected in impacted zones. On the other hand, the microbial processes also respond to organic enrichment by enhancing their activity, and thereby increase the risk of hypoxia and reduced conditions in the sediments. Occurrence of hypoxia affects the benthic fauna negatively, but areas where hypoxia occurs are frequently areas that are stagnant or with poor water exchange (Gray, Wu and Or, 2002). Thus, hydrographic factors are key processes determining whether or not hypoxia occurs. Offshore and off-the-coast locations should have less risk of hypoxia, although local hydrographic conditions have to be considered. Furthermore, deep-dwelling benthic fauna, which are expected to be abundant in deep sediments, may suffer from sulfide toxicity at higher oxygen concentrations, due to reduced conditions in the sediments (Hargrave, Holmer and Newcombe, 2008).

A major difference between shallow and deep water is a lower biomass of benthic fauna with lower bioturbation activity in the later (Snelgrove and Smith, 2002). Studies of bioturbation activity in deep sediments are few, possibly constrained by the high costs and difficulties of operation under such conditions (Hughes and Gage, 2004). Importance of bioturbation activity has been studied experimentally in fish farm sediments (Heilskov, Alperin and Holmer, 2006; Heilskov and Holmer, 2003; Valdemarsen, Kristensen and Holmer, 2009). The extent of bioturbation plays a major role in the supplement of electron acceptors to complement the microbial processes (Valdemarsen, Kristensen and Holmer, 2009) and a lower activity may lead to a depletion of e-acceptors and a shift in the bacterial processes from dominance of aerobic respiration to sulfate reduction and possibly methanogenesis, if sulfate is depleted (Holmer and Kristensen, 1994). Enhanced sulfate reduction, and thus sulfide production, may eliminate the benthic fauna as a result of reduced conditions and anoxia (Hargrave, Holmer and Newcombe, 2008). This is particularly a problem in the fine-grained sediments with low advection, and also a potential problem in coarse-grained deep sediments due to low iron pools (Valdemarsen, Kristensen and Holmer, 2009). Heilskov, Alperin and Holmer (2006), however, found limited accumulation of sulfides in coarse-grained carbonate fish farm sediments stimulated by high bioturbation activity, whereas high sulfide concentrations were found in the similar sediments, when no fauna was present (Holmer and Frederiksen, 2007). Unpublished results from Norway show low accumulation of organic matter, if any in coarse-grained sediments, since the organic material is transported away from the farming sites (R. Bannister, personal communication, 2010). Deposition of organic material in shell sand can potentially lead to dramatic effects, since the presence of benthic fauna is likely low in these carbon limited sediments, and microbial degradation will probably be the dominant degradation process for the deposited organic material. Advection of exposed sediments can provide e-acceptors to the bacteria, while a lack of advection may result in a shift towards reduced conditions with high sulfide pools, as shell sands have limited capacity to bind sulfide with iron (Holmer and Frederiksen, 2007). Shell sands contain low levels of iron due to their carbonate nature. Due to the potential large dispersion of waste products from marine aquaculture at exposed locations, it is important to monitor far-field effects in nearby sedimentation basins, which are likely receivers of dispersed organic matter, although the sedimentation is expected to be less than at coastal sites.

Sedimentation of waste products in areas experiencing seasonal or annual oxygen depletion events should clearly be avoided, as organic matter inputs can increase the duration and extent of oxygen depletion, and as the frequency and distribution of these zones are increasing rapidly in coastal zones of industrialized countries (Diaz and Rosenberg, 2008), this is important to consider when planning aquaculture expansion. In contrast to deep sediments, there are more experimental enrichment studies of shallow sediments, and some of them have focused on the fate of fish farm waste products (see above). Generally these studies show extreme high rates of bacterial decomposition, stimulated by the high nutrient contents of the waste products. The nutrient contents and bacterial lability of the organic matter in feed pellets and faeces are much higher compared to phytoplanktonic detritus, concentrating the supply of organic matter to the sediments even at relatively low rates of sedimentation and enhancing microbial degradation much more that marine derived organic matter (Valdemarsen, Kristensen and Holmer, 2009). Most studies have been undertaken either in defaunated sediments or in sediments with relatively tolerant benthic fauna, such as polychaetes of varying size. These studies show a certain capacity for decomposition of organic waste products, but the capacity is very limited in defaunated sediments leading to accumulation of organic matter. With fauna present the capacities vary with sedimentation regime and abundance, biomass, bioturbation mode and diversity, and a range of threshold values for maintaining the benthic communities in enriched sediments have been determined (Findlay and Watling, 1997; Kutti, Ervik and Hoisaeter, 2008; Valdemarsen, Kristensen and Holmer, 2009). Similar experiments will be useful for the deep sea sediments, and one of the first issues to include, is the fact that both benthic fauna activity as well as microbial activity can be up to several orders of magnitude lower than found in coastal sediments. This may affect the threshold values for organic matter decomposition significantly towards lower enrichment tolerance.

Observed impacts on benthic conditions

Norway has quite some experience with fish farming in deep water, and on both protected and exposed sites, but unfortunately only few of the results have yet been published, and only from protected sites (Kutti, Ervik and Hansen, 2007; Kutti, Ervik and Hoisaeter, 2008; Kutti *et al.*, 2007). Kutti *et al.* (2007) found an enriched benthic fauna despite limited or no organic enrichment of the sediments. Examination of long-term data sets indicate relatively longer time before an enrichment of the sediments is observed compared to sites at shallower depth, but over time, the sediments become enriched, when no fallowing is practiced (K. Hansen, personal communication, 2010). Since the sediments are carbon limited, they have an immediate capacity to turn over the organic matter due to the stimulation of the associated benthic organisms (fauna and bacteria) compared to coastal sediments, which respond negatively to further enrichments (Hargrave, Holmer and Newcombe, 2008). As the benthic fauna present at a given fish farm location often reflect local conditions (bottom habitat, larval supply, sedimentation regimes and connected habitat types), initial abundance, biomass and diversity may be quite different between farms (Levin *et al.*, 2001). It is therefore, difficult to generalize observations from a single study, and assimilative capacity of the sediments may vary substantially between sites. Comparison between many farms showed that the benthic fauna communities tend to change towards a more organic tolerant community and the fauna community in impacted sediments is often more uniform between farms after years of fish farming compared to initial or pre-farming conditions (R. Bannister, personal communication, 2010). The organic tolerant communities are dominated by small polychaetes such as *Capitella* spp., which is a widely distributed species (cosmopolitan), also at these depths (>50 m). *Capitella* spp. seem to generate their own environment by increasing the reduction of the sediments and increasing organic matter pools in the surface layers, resulting in high abundances of this particular species in expense of less tolerant species (Heilskov and Holmer, 2003).

At the New Hampshire (USA) test sites benthic impacts have been investigated, and factors such as biodiversity and abundance of infaunal and epifaunal communities and sediment organic buildup were used as indicators to track environmental impacts (Ward, 2004). The results showed no obvious trends for any of the univariate benthic fauna community data (density, biomass, taxonomic richness) or the ratios of pollution tolerant/intolerant taxa relative to the predicted pollution effects zones in two separate sampling periods (spring and fall). There were a couple of marginal effects with lower diversity and mean taxa numbers at one study site and it was suggested that this could be an early signal of increased organic loading to the sediment under the cages, but density and biomass increases were not observed. The densities of pollution tolerant taxa (oligochaetes, capitellids, cirratulids, ampeliscids) and pollution intolerant taxa (nuculids, paraonids, ampharetids) were calculated and compared, and pollution intolerant taxa were in the majority at all 20 study sites, with only one sample where pollution tolerant taxa represented >50 percent of the fauna. Rankings by taxa also showed very similar trends across four pollution effects zones, with spionid polychaetes and nematodes dominating in all four zones, followed by nuculid bivalves and paraonid polychaetes (both pollution intolerant taxa) in most areas for both spring and fall sampling periods. These data suggest that the benthic communities in all four zones were dominated by infaunal taxa that are relatively intolerant of organic pollution, suggesting no or only minor impacts on the seafloor. The study also calculated various ecological indices and the results showed similar values for samples from all four zones, confirming that no impacts on benthic communities were detectable. In addition, the loss-on-ignition values for spring and fall sampling of the sediments did not indicate a buildup of organic debris in the sediments.

The bottom sediments at the New Hampshire test site were also surveyed in a long-term study, and showed no seasonal or year to year variations in sediment grain size or organic matter content measured as loss-on-ignition (Ward, 2004). There was no consistent change in the organic content of the bottom sediments since the beginning of the monitoring period in 1997 until 2006 suggesting no detectable change in organic matter pools in the sediments. Videography cruises were done to track possible changes in benthic epifauna during one sampling event. Here an increase in the number of northern sea stars was found, which was partially related to cleaning of biofouling from fish cages. The organisms and organic debris removed from the cages while cleaning provide a short-term food source attracting scavengers such as sea stars. The high numbers of sea stars could also be related to a strong storm activity that occurred just before the survey. The strong bottom currents associated with a storm may have scoured the bottom causing some bivalves to be exposed, providing a food source for scavengers. The survey indicated more shell debris on the seafloor at most of the stations, which could be related to storm activity and bottom scouring. In either case, once the temporary food supply was depleted, it is likely the northern sea stars dispersed. Statistical analysis showed no significant differences in epifauna among four impact zones for both spring and fall sampling periods. Hence, no enrichment effects that occurred consistently across the impact zones were detected in the epifauna data.

In contrast to the few observations of offshore farms, studies in the off-the-coast category (Table 3) consistently show an organic enrichment of the sediments, conditioned by the dominant flow directions. Furthermore the benthic fauna is generally disturbed, but to varying extent (little or a lot) and the faunal diversity lower compared to reference sites. The benthic secondary production may well be higher, enhanced by organic matter inputs. The organic input increase bacterial production, which reduces the sediment, and the fauna found in off-the-coast sediments is more pollutant tolerant, typically dominated by small polychaetes. As an example, a study of a submerged off-the-coast/offshore farm in the Caribbean showed a weak organic enrichment in the dominant flow direction, while the benthic fauna had lower abundance under the net cages. At an aquaculture farm used for the fattening of Atlantic bluefin tuna (*Thunnus thynnus*), located at an exposed site (700 m from the coast, average bottom depth of 45 m and average current speed of 6 cm s^{-1}) in the Mediterranean Sea, Vezzulli *et al*. (2008) found no substantial differences between farm and control sites. Deviations of farm values from control values, when they occurred, were small and did not indicate any significant impact on either the pelagic and benthic environment. Deviations were more apparent in the benthic compartment where lower redox potential values, higher bacterial production rates and a change in nematode genus composition pointed out to early changes in the sediment metabolism. In addition, indigenous potential pathogenic bacteria showed higher concentration at the fish farm stations and were a warning of an undesirable event that may become established following aquaculture practice in oligotrophic environments. Other studies at shallower depth have shown more significant impact with organic matter enrichment of the sediments, increased bacterial activity, reduction of the sediments and deteriorated bottom fauna (Table 3). Water depth seems to be a key factor of the benthic impacts, modified by local production and hydrodynamic conditions.

Attraction of wild fish to off-the-coast and offshore farms may further modify the benthic impact. Studies at off-the-coast farms in the Mediterranean have shown less benthic impact due to lower rates of sedimentation (Vita *et al.*, 2004b). Similarly, Svane and Barnett (2008) found that scavengers, such as leatherjacket and isopodes, reduced the accumulation of trash feed under tuna farms in South Australia. Enrichments in the motile epibenthic fauna may on the other hand predate on the infauna and reduce their abundance and bioturbating activity (Sanz-Lazaro and Marin, 2009). Reduced bioturbation limit the exchange of metabolites and e-acceptor, which potentially accumulates organic matter due to inhibition of microbial processes like sulfate reduction. Sanz-Lazaro and Marin (2009) found accumulation of organic matter at this off-the-coast farm compared to reference sites, indicating lower decomposition capacity.

Fallowing has been used successfully for coastal aquaculture, where the sediments are left to recovery for 6–12 months (Macleod, Moltschaniwskyj and Crawford, 2006), but some sites seem to recover faster than others (Macleod, Moltschaniwskyj and Crawford, 2008). Fallowing for up to 36 months only recovered the benthic fauna community at a site, which was naturally organic rich, whereas a more oligotrophic site failed to recover probably due to the lack of organic tolerant species present (Macleod *et al.,* 2007). Fallowing for six months was also examined at an off-the-coast location, where the community structure at affected sites became more similar to communities at distant reference sites (Lin and Bailey-Brock, 2008). Additionally, a sudden disappearance of enrichment indicator species at previously affected sites during the fallow period suggested the beginnings of a recovery. However, species diversity did not increase significantly during the fallow period, indicating that the affected communities were not fully restored to pre-culture or distant reference conditions. Both studies demonstrate the potential environmental benefits of scheduled fallow periods or crop rotations in off-the-coast and possibly also in offshore aquaculture.

Sensitive habitats

Moving aquaculture further out from the coast and to deeper waters will remove the pressure on coastal sensitive habitats, but that does not mean that there are no sensitive habitats on potential off-the-coast and offshore sites. Especially off-the-coast locations will still have representation of sensitive coastal habitats, especially in areas with clear water and deep light penetration, for example in the Mediterranean Sea, where seagrasses and macroalgae are still present at 50–70 m water depths.

Hard substrate, though rare on the continental shelf, where offshore activities are planned, are the most familiar habitats to the general public due to their photogenic biota. Bedrock, boulders and cobbles can be found in a gradient of physical conditions from high to low stress. They offer a number of microhabitats, dominated by particle feeders such as sponges, bryozoa and sea squirts. Many commercially important fishes utilize boulder reefs in their juvenile stages. Soft-sediments are widespread in deeper waters (>50 m), but due to the high costs associated with studying these habitats presence of sensitive habitats is not well studied. Soft sediments are formed from finer particles such as silts and muds settling out due to reduced physical forcing, in particular in basins and sheltered sites (Levin *et al.*, 2001). The epifauna tends to be sparse in such areas with few sessile emergent species (mainly anemones and sea pens) and low abundances of mobile scavengers (Carney, 2005). In the northern Atlantic Sea the fauna is typified by burrowing megafauna that shape the surface of the seabed with burrow entrances and mounds of excavated sediment and faeces. The fauna is dominated by crustaceans, typically callianassids and in some areas with important commercial fisheries, such as the Norway lobster (*Nephrops norvegicus*) and hyperbenthic pandalid shrimps. These species are highly sensitive to hypoxia, and for Norway lobster slight changes in oxygen concentrations in the water column may negatively affect behaviour and increase mortality, which influence both recruitment and recolonization potentials (Eriksson and Baden, 1997).

Biogenic reefs are formed by mussels (oysters, mussels), polychaetes (*Sabellaria* spp.), corals and sponges. In addition to their role in transferring energy to the seabed, biogenic structures greatly contribute to marine habitat complexity by increasing the three dimensional relief of seabed topography and often have a nursery function for juvenile fishes and crustacean. As biogenic reefs are constructed primarily by living organisms, they are particularly vulnerable to physical disturbance, fishing or pollution effects associated with eutrophication. An example of deep sea sensitive habitats is from the North-East Atlantic, where the dominant reef-framework forming coral species, *Lophelia pertusa* and *Madrepora oculata*, form a symbiotic association with the polychaete worm *Eunice norvegica*, and these reefs are considered highly sensitive to anthropogenic activities such as increased sedimentation due to the delicate filtration apparatus of these corals (Dolan *et al.*, 2008). Recently large reef like formations of sponges have been found in the North Atlantic (Klitgaard and Tendal, 2004). Sponges filter particles from the water column and while small enhancement of particle load possibly is tolerable, higher loading rates may inhibit the filtration by clogging the pores.

Observed impacts on sensitive habitats

Calcified macroalgae are distributed in marine habitats from polar to tropical latitudes and from intertidal shores to the deepest reaches of the euphotic zone (Nelson, 2009). These algae play critical ecological roles including being key to a range of invertebrate recruitment processes, functioning as autogenic ecosystem engineers through provision of three-dimensional habitat structure. Calcified macroalgae contribute significantly to the deposition of carbonates in coastal environments. These organisms are vulnerable to human-induced changes resulting from land and coastal development, such as altered patterns of sedimentation, nutrient enrichment through sewage and agricultural run-off, and are affected by coastal dredging and aquaculture. It is not yet understood how interactions between a range of variables acting at local and global scales influence the viability of calcifying macroalgae and associated ecosystems. In Scotland, the movement of farms away from enclosed sites to areas with strong tidal flow has resulted in locating farms over calcified macroalgae (termed "maerl"), characterized as a habitat for a diverse array of benthic crustaceans (Hall-Spencer *et al.*, 2006). Monitoring at a farm located over a maerl bed for 12 years showed a die-back of living maerl, periods of anoxia and an accumulation of organic material on the seabed within 25 m of the cages. Assessments of crustacean assemblages showed significant reductions in biodiversity near the farm. Some scavengers (e.g. the amphipod *Socarnes erythrophthalmus*) were far more abundant near the cages than at distances >75 m from the cages, but many small crustaceans (e.g. the tanaids *Leptognathia breviremis*, *Typhlotanais microcheles* and *Psudoparatanais batei*; the cumaceans *Nannastacus unguiculatus*, *Cumella pygmaea* and *Vaunthompsonia cristata*; and the amphipod *Austrosyrrhoe fimbriatus*) were impoverished near the cages, probably due to combined effects of organic wastes and the use of toxins to combat parasitic copepods. The study concluded that farming should not be carried out at sites where long-lived biogenic habitats such as maerl occur because this will likely increase the area of habitat degradation.

Escapees and genetic interactions

Increased production of cultured fish increases the potential of huge escapes and inadvertently introductions into the wild. Compared to coastal aquaculture, off-the-coast and offshore farms are projected to increase significantly in size and being located under conditions with exposure to strong winds and high seas, the risk of release is increased. This is a challenge to the technological development, and the use of submerged cages located at depths below the immediate wave zone is one solution to reduce the risk of damage of net cages. If an escape occurs, which could also be due to attack by large predators, the release of fish to the ocean is likely to be high. One single submerged cage may contain up to 25 000 full-grown fish. Most of the current knowledge on escapees and genetic interactions is from salmon farming (Cross *et al.*, 2008). Salmon is an anadromous migrating to freshwaters for breeding and in this way quite different from most other marine fish, which have their entire life cycle in marine waters. Cultured strains interact genetically with natural populations directly by interbreeding or indirectly by modifying the ecosystem (e.g. ecological competition, spreading of disease). Cultured strains have lower fitness in the wild, and interbreeding with wild populations may thus reduce the overall fitness. In Chile, where salmon was introduced in aquaculture around 1980, escapes are found in local rivers and exert ecological and social pressures on the ecosystems and are a major challenge for the managers (Soto *et al.,* 2007; Soto, Jara and Moreno, 2001). Another example of introduced species is the oyster *Crassostea gigas*, which has caused major indirect impact upon the introduction to Europe, where it is competing ecologically with *Ostrea edulis* and *Mytilus edulis* in major estuaries in Northern Europe. For fishes, indirect interactions may decrease genetic variability and alter genetic composition of the wild stocks. The genetic interactions are considered at greatest risk when reared species outnumber the wild stocks. This is only the case for a few species, such as salmon in North Atlantic where the reared species are about two orders of magnitude higher than wild, whereas most other species (e.g. cod, bream, bass and mussels) are more abundant in the wild. Salmon is even more at risk due to the local adaptations of the strains, where genetic interactions can cause major loss of ecological performance. This risk is less for the marine species, but considering the expected increase in aquaculture production and the continuous reports on overfishing may increase the problems. Intensive culturing of seabream along the Hellenic coast in Greece has increased the landings with up to 80 percent indicating a major impact on the fisheries of this particular species in the area (Dimitriou *et al.*, 2007).

The main risks by off-the-coast and offshore farming are thus the increasing size of the farms and their exposure, increasing the potentials of major and regular losses, which has been identified as important bottlenecks for genetic impacts (Cross *et al.*, 2008). Although the farms are located farther from shore, it is still relatively close, e.g. within a few kilometres, and it virtually means that there are the same risks of direct and indirect interactions with wild fish populations as found in coastal aquaculture. Only if the farms are located in open seas, e.g. hundreds of kilometres away, interactions would be less, in particular if the farms are located away from major routes of migration and feeding and spawning grounds. Interactions with wild populations are affected by a range of factors, such as season where for example escape of salmons at the same time as the wild populations migrate to the spawning grounds have major direct (interbreeding) and indirect effects (ecological competition) on the wild fish. Interactions for seabream and seabass are less known, but are assumed to be less compared to salmon due to more abundant native populations and the lack of local adaptations, such as homing behavior for salmon. The degradation of the wild strains due to genetic interactions could be avoided by using sterile or triploid fish, and although this method is currently been developed, there are many difficulties and uncertainties to be solved for a variety of species. Only few successful examples have been provided so far.

Observed genetic interactions

In Norway, the stock of farmed Atlantic salmon greatly exceeds that of wild conspecifics (Gross, 1998). Although a relative small proportion of farmed salmon escape, the number is large relative to the population of wild salmon. In recent years, the number of farmed salmon in reported Norwegian salmon catches has been estimated to be between 30 000 and 60 000 annually (Hansen, 2006). Spawning of escaped farmed salmon in wild salmon rivers has been documented, and introgression of farmed salmon into wild populations may have negative effects (McGinnity *et al.*, 2003; McGinnity *et al*., 2004). If salmon move randomly after they escape, they may be "trapped" in the fjord system in which the farm from which they escaped is located and enter rivers within that system. This is one of the reasons that salmon farming in Norway has been restricted or prohibited in some areas close to important salmon rivers. Another reason is to reduce the risk of pathogens and parasites spreading from farmed to wild salmon populations (Bjorn and Finstad, 2002; Finstad *et al.*, 2000). Significant positive correlation between the incidences of escaped farmed salmon in the nearby rivers and the intensity of salmon farming has been found (Fiske, Lund and Hansen, 2006). As both the distance to rivers and the size of the farm are important for the encountering of escapes in natural habitats, it is only by moving to offshore location a lower pressure on wild populations can be expected. However, one third of the production of salmon occurs in areas, where it is exotic, and spawning of escapes have not been detected so far, suggesting limited genetic interactions in these areas (e.g. Chile and Tasmania [Australia]) (Thorstad *et al.*, 2008).

Disease

Diseases and virus can be both introduced and transmitted through aquaculture. Without proper controls and quarantines, it is possible for diseases or parasites to be introduced to a region through the importation of juveniles. In cases of disease outbreak on a farm, the disease can be transmitted to the wild if it is an open production system. Just as pathogens and parasites can be transferred from farms into the wild, disease free farmed species can be infected from the wild and in open production systems there is flow in both directions. Diseases can also be transmitted from farm to farm, and the salmon industry in Chile has almost collapsed due to severe virus outbreak causing the disease infectious salmon anemia (ISA). Spread of disease and virus between farms are correlated with production in a given area, and especially distances between farms and local currents are important. A relocation of farms to more exposed sites can therefore be expected to reduce the spread of disease and virus between farms. On the other hand, the increase in size of the farms may increase the risk of spreading the disease to a high number of fish, and outbreak at a single farm could have more impact. The spread of disease will depend on distances to major migration routes, and to feeding and spawning grounds, as well as the attraction of wild fish to the cages. Introduction of diseases from wild fish will depend on the wild populations and abundance of fish in the area. In a productive fishing area, the pressure will be much higher compared to less productive areas, where the last would be a typical offshore area. Disease introduction and transfer can also be a concern in shellfish and seaweed culture systems (Boyd *et al.*, 2005).

There is a range of known bacterial diseases affecting marine aquaculture, and efficient vaccines have been developed for some of them, whereas others have to be treated with antibiotics. Many bacterial strains are resistant to a number of therapeutics such as oxolinic acid, and the development of new antibiotics is an on-going process (Avendano-Herrera *et al.,* 2008). Use of antibiotics has environmental impacts, both by spreading to wild fish attracted to the cages and on the bottom habitats (Samuelsen *et al.*, 1992; Samuelsen, Torsvik and Ervik, 1992), and as the use of medicines is expected to decline in offshore farming, this risk should be minimized.

Biofouling

Marine fouling occurs globally and is a process that has always plagued mariners, whereas fish farming is a relatively young industry in comparison. Fish farm fouling is a growing, global phenomenon (Hodson, Burke and Bissett, 2000) and it is widely accepted that fouling in the aquaculture industry is an expensive problem (Hodson, Lewis and Burke, 1997). There are several positive attributes of biofouling, such as seeding mussels and filtration of the water column for particulate waste products. However, the effects of biofouling in aquaculture are largely detrimental. Hydrodynamic forces on a fouled net can be up to one order of magnitude higher than on a clean net. It can cause physical damage to the net, disruption of water flow and thereby limiting nutrient exchange and waste disposal. Indirect costs are for cleaning and repairs, and as much as US$40 000 is spent annually on removal of the fouling community from the two fish cages at the New Hampshire Open Ocean Aquaculture site (Greene and Grizzle, 2007). Removal of these organisms is necessary because of their effects on cage behavior, including the potential for causing the cages to sink. Hence, these organisms are viewed mainly as a nuisance in aquaculture. However, the fouling community potentially removes dissolved nutrients and suspended waste materials from the cages because the community includes plants and suspension feeding invertebrates.

By moving the farms to off-the-coast and in particularly offshore locations, where the nutrient availability, productivity and seed dispersal in general is expected to be lower, less biofouling can be expected. On the other hand, the increase in farm size and use of more feed, may increase biofouling intensity on the farming structures by cosmopolitan species such as barnacles and mussels. Furthermore, as the maintenance of the farms will be much more difficult and expensive and simple solutions as exchanging nets, which is done frequently in coastal farming to avoid fouling, is not possible, biofouling intensity may increase. Biofouling can be reduced by the use of chemicals, such as antifouling paints, and is probably investigated as a solution as long as negative effects on the cultured fish are avoided (Braithwaite, Carrascosa and Mcevoy, 2007).

Observed biofouling

Fouling of fish farms is influenced by number of factors, such as cage age and net texture, water depth, complexity, inclination and position in the water column. Greene and Grizzle (2007) deployed experimental nets at an open ocean fish farm in New Hampshire at different times of the year and for different durations. They found substantial and significant differences in density and biomass of the total communities of most successional sequences when comparing warmer to cooler months. *Mytilus edulis*, the blue mussel, dominated in density and biomass, and other less abundant species were amphipods (*Caprella* sp. and *Jassa marmorata*), molluscs (*Hiatella arctica* and *Anomia* sp.), the seastar *Asterias vulgaris*, and the anemone *Metridium senile*. Juveniles and adults of some species were also present in some early (1-month) successional sequences, indicating that migration may be an important process in community development. Some of the dominant species were present in all successional stages (early, intermediate and late), differing only in relative abundances in the community. The consistent dominance of *M. edulis*, and other differences in successional patterns compared to what has been typically observed for epifaunal communities in the region, were hypothesized to be the result of a combination of factors: a lack of predators such as seastars and fish that typically consume mussels in natural communities, excessive predation by nudibranchs on those species (e.g. *Tubularia* sp.) normally abundant in early successional stages, year-round availability of mussel larvae, and cage cleaning protocols that do not remove all the organisms present. The introduction of predatory fishes or seastars into or onto the cages might provide some control on the growth of fouling organisms.

Langhamer, Wilhelmsson and Engstrom (2009) studied an offshore wave power test station located two kilometres from the coast in west Sweden. Due to the depth of the foundations (25 m) and high water turbidity causing low light intensity, they found only few filamentous low-light adapted red algae. The colonization of the foundations was homogeneous, consisting of mostly barnacles and serpulid tubeworms. The primary colonization mainly comprised tubeworms and barnacles that are opportunistic and short lived. The second assemblages were more heterogeneous, and secondary colonizers, such as ascidians, had outcompeted the primary ones by overgrowing them and probably preventing them from feeding successfully. Epifaunal assemblages can form new habitats for smaller organisms (*Idotea* sp., *Jassa falcata* and *Jassa pusilla*), and constitute feeding grounds for larger predators (*Asterias* sp., *Cancer* sp.). Fish abundance was low compared to other more complex structures in shallower water in adjacent areas, probably mediated by a high abundance of *Cancer pagurus*. Lobsters were also present, but only in cavities under the foundations.

Parasites

Due to the intensity of culturing fish in cages, the risk of spreading parasites within the farm is high, compared to wild fish. On the other hand, due to the use of artificial feeds, the trophic transfer of parasites is less, although fishes farmed in net cages may become infested by parasites from wild fishes and in turn become point sources for parasites (Krkosek *et al.*, 2007; Nowak, 2007). Sea lice, copepods of the family *Caligidae*, are the best-studied example of this risk. Sea lice, the most significant parasitic pathogen in salmon farming in Europe, the United States of America and Chile, are estimated to cost the world industry US$300 million a year and may also be pathogenic to wild fishes under natural conditions. Juvenile (copepodite and chalimus) stages have repeatedly occurred on juvenile wild salmonids in areas where farms have sea lice infestations, but have not been recorded elsewhere. There is increasing evidence that lice from farms can be a significant cause of mortality on nearby wild salmon populations, but they could also infect other wild fish (Marin *et al.*, 2009). In the case of salmon, the ecological impact of parasite transmission from fish farms is mediated by the migration of wild fishes, which determines the period of exposure to parasites (Krkosek *et al.*, 2009). When the exposure period lasts for several weeks, as occurs when juvenile salmon migrate past salmon farms, it is predicted that lice accumulate to abundances that can elevate salmon mortality and depress salmon populations. High parasite loads on seaward-migrating salmon smolts have been implicated as a potential cause of high mortality at sea and reduced return of adults to rivers (Bjorn and Finstad, 2002; Bjorn *et al.*, 2007). Moving farms to off-the-coast and offshore locations is expected to reduce the infections by parasites, as least between farms, due to the larger distance between farms. Also to wild fish, in particular if farms are sited in locations away from migration routes, feeding and spawning areas.

Parasites are also a problem for shellfish farming, and Buck *et al.* (2005) found that mussels taken from offshore sites (e.g. buoys, platforms) were free of trematodes and shellboring polychaetes, suggesting reduced risk of parasite attack. Parasitic copepods only occurred at a single offshore site, on a 20-year-old research platform, but not on buoys or collectors exposed for shorter time periods. Through a variety of detrimental effects, trematodes, parasitic copepods and shell-boring polychaetes are known to affect growth performance and product quality. Buck *et al.* (2005) therefore, proposed that offshore mussel production could be a promising culture procedure because it seems to result in lower parasite burden than at traditional culture sites. Whether offshore production also results in better survival and growth, compared with inshore mussel culture on a commercial-scale, needs to be investigated further.

Wild fish attraction and predation

Coastal aquaculture farms have considerable demographic effects on wild fish by aggregating large numbers in their immediate vicinity. Dempster *et al.* (2005) found that seabream and seabass farming in Mediterranean attracted wild fish assemblages that had up to 30 different species and estimated that the aggregation biomasses ranged between 10 and 40 tonnes at five of the nine farms investigated (Dempster *et al.*, 2004). Similarly large aggregations have been noted in Greece (Thetmeyer, Pavlidis and Chromey, 2003) and the Canary Islands (Boyra *et al.,* 2004; Tuya *et al.,* 2006). Mussel rafts in the Mediterranean Sea (Brehmer *et al.,* 2003) are also known to aggregate wild fish, whereas cold water farms in the North Atlantic attract less species (Dempster *et al.,* 2009). Large aggregates of saithe have been found consistently around salmon farms showing a distinct morphology compared to natural fed species, and gadoid fish are abundant with on average 10.2 tonnes per salmon farm in Norway (Dempster *et al*., 2009).The fish populations in the Mediterranean are dominated by a few primarily planktivorous fish, feeding on feed pellets. Also demersal fish are attracted to fish farms, although aggregations vary in numbers and species. Several observations of large predatory fish feeding on the smaller fish aggregated at the farms have also been observed. Fish farms are attractive habitats for certain species of wild fish in specific seasons, and aggregates are considered temporal stable only over weeks or a few months, although for some areas only limited seasonal variation has been found such as in the Canary Island (Boyra *et al.,* 2004). Also large spatial variability in aggregates can be found in same waterbodies for no obvious reasons (Dempster *et al.,* 2002). Adult fish of reproductive size generally dominate the assemblages, and stomach content analysis has revealed that 66–89 percent of fish consumed feed pellets lost from the cages. Wild fish may consume up to 10 percent of the pellets used at farms, indicating that food is a key attractant. High abundance of attracted fish may significantly reduce the environmental impacts of fish farming by reducing the sedimentation of waste products (Vita *et al.,* 2004b), but their own excretion of ammonium and leaching of inorganic and organic nutrients from faeces contributes to nutrient availability around farms (Fernandez-Jover *et al.,* 2007). Furthermore, increased levels of parasites and disease in wild fish are potential impacts of the dense and temporally persistent aggregations present in close proximity to large biomasses of caged fish hosting parasites and diseases (Dempster *et al.,* 2002). The presence of predator fish is less well documented, but in the Mediterranean *Pomatomus saltatrix*, the bluefish, has been observed to predate on seabream, when present inside the cages and on attracted fish when present outside (Sanchez-Jerez *et al.,* 2008).

Off-the-coast and offshore farms will most likely also attract fishes in large numbers due to the increase in size and potential increase in loss of feed pellets. This is particularly the case if the farms are located close to the shore or near to migration routes, feeding and spawning grounds. A major concern of offshore farms is the attraction of large predatory fish such as sharks and killer whales. On the Pacific coast of the United States of America and Canada, the Californian sea lion *Zalophus californianus*, the harbour seal *Phoca vitulina* and Steller and the sea lion *Eumatopias jubatus* interact with coastal fish farms by predating upon salmonids inside the cages while damaging netting in the process (Nash *et al*., 2000). On the Atlantic coast, harbour seals and the grey seals *Halichoerus grypus* cause similar problems (Nash *et al*., 2000). In Chile, negative interactions of sea lions (*Otavia flavescens*) with salmon farms have been described (Sepulveda and Oliva, 2005). Sea otters have also caused conflicts with production in specific regions (e.g. Freitas *et al*., 2007).

A final aspect of wild fish interaction is demonstrated in a meta-analysis by Ford and Myers (2008) of wild fish mortality in areas with farming compared to without. They find a surprisingly and significantly reduced survival (>50 percent) of wild fish in areas of intensive fish farming possibly explained by the environmental interactions mentioned in this review (e.g. genetic, environmental, disease). Whereas fish attracted to the cages may benefit from the surplus feed, others closely related species may suffer from intensive farming.

Chemicals and medicines

A variety of chemicals are also used in marine aquaculture, including disinfectants, antifoulants, sea lice treatments and veterinary medicines (Costello *et al.*, 2001; Read and Fernandes, 2003). Zinc, cadmium and copper have been used as tracer of feed pellets (Dean, Shimmield and Black, 2007), while copper also is used as antifoulant. All three metals accumulate under net cages, but to a larger extent than accounted for in the feed, suggesting other sources of metals (Dean, Shimmield and Black, 2007; Sutherland *et al*., 2007). The environmental impacts depend on the chemical or medicine in use. Antifouling metals, e.g. copper, tributyltin (TBT), accumulate in the sediments and benthic organisms and are transferred to the food chain. They may also affect the bacterial processes in the sediments (Mayor *et al.*, 2009) and show toxicity on the benthic organisms (Mayor *et al.*, 2008). The impacts of anti-microbial compounds can be summarized as effects on non-target organisms, effects on sediment chemistry and processes, and the development of resistance (Beveridge, Phillips and Macintosh, 1997). As discussed above, the use of chemicals as antifoulants may increase in off-the-coast and offshore farming, whereas the use of medicines is expected to decrease. The impacts of antifoulants will probably be quite similar with an accumulation in the sediments, but over a larger area due to larger dispersion. Very limited information is available on possible impacts of metal contamination of deep sea sediments.

INTERACTIONS WITH OTHER SECTORS

Current policy and spatial planning for aquaculture and other sectors tends to rely on separation and exclusion principles (Douvere and Ehler, 2009). That is, capture fisheries and aquaculture operations or wind/wave farms and aquaculture operations may be restricted to exclusive zones. Typically, such decisions have arisen out of concern for either ecological preservation or as a result of stakeholder conflicts (Holmer *et al.*, 2008). Exclusion and separation are at best partial solutions to planning challenges in the future. By addressing one or a limited number of sectors (usually those in conflict with each other) at a time, they may in fact not fully consider the range of impacts originating from the wide variety of resource uses. Moreover, they may ignore potential synergies between different stakeholders and the potential for mutual benefit.

Capture fisheries

Environmental interactions with capture fisheries expand a wide range including enrichment of habitats, increased fisheries biomass, decrease in fisheries due to negative genetic effects, damage to fisheries due to the introduction of exotic species, competition for space and fishing of fish for aquafeeds. Furthermore, certain environmental and spatial interactions are likely to vary over time or will not be evident until after a farm is established, such as changes in water quality characteristics or how commercial fisheries interact with aquaculture activities (Dempster *et al.*, 2005). Management measures may therefore, need to be location-specific and adaptive.

The environmental impact of capture fisheries has been extensively studied and its role in changing marine biodiversity, decline of wild fish stocks and interactions with other marine and coastal zone stakeholders are well described. Much of the research on the interaction between aquaculture and capture fisheries focuses, however, on uni-directional negative impacts stemming from the latter. At the stakeholder level, one of the major conflicts between coastal fisheries and aquaculture operations is on the grounds of space and regulation is on the basis of separation and exclusion. This component is considered to be of less importance when moving farms offshore. Given the evidence that aquaculture may actually stimulate fisheries at local and, in some circumstances regional level, at least in oligotrophic areas, there may be further scope for avoiding long-standing conflicts by exploiting synergies. Equally important, it will be possible to assess the relative ecological significance of aquaculture and capture fisheries operations together with other activities and tailor spatial planning accordingly. Social acceptance by stakeholders during site selection and initiation is important, and also the economic competition between aquaculture and fisheries due to the growth in scale of existing aquaculture farms, altering the balance between the two market sectors is of major concern in some areas.

The spatial location and stock alteration produced by aquaculture farms (including the catch of feed fish) may alter the harvest of the fishing vessels. In some cases, it is the same commercial fleet in the area that fishes for the feed fish for the farms during some periods of the year. This has clear implications on employment, which at the same time may alter local acceptance of aquaculture (Whitmarsh and Palmieri, 2009). In other cases, it is just the changes in the wild stock produced by increased demand for aquafeeds. However, the influence of aquaculture on the stock of feed fish also targeted by extractive fisheries may be modified indirectly by the use of more sophisticated integrated aquaculture techniques (Newkirk, 1996). Asche and Tveteras (2004) analysed the impact on wild fish stocks induced by the global demand for manufactured feed, and conclude that the problem stems mainly from open-access fisheries and that without proper management, expanded growth in aquaculture as well as other sectors using fish feed (e.g. poultry) could put additional stress on wild fish stocks by increasing the demand for feed. This aspect will be addressed further below.

Economic interactions between fisheries and aquaculture happen in different ways. From the moment of production/extraction to the exchange in the market, through the distribution logistics and future planning of the activity, fisheries and aquaculture are interrelated through several links and involve a number of different stakeholders. Beyond production of fish, the landing, transport and processing of fish from both aquaculture and extractive industries follow the same channels, and the sign of this interaction will depend on how saturated they are. The same occurs with fish promotion/marketing. The actual result of the interaction depends on the present demand for fish. The interactions between the prices of the fish from both origins and their complementary/substitutive nature depending on their quality and seasonal availability are also important aspects. An additional interaction exists in the labour market, where qualifications needed for fisheries and aquaculture may be complementary. The establishment of new aquaculture farms also increases the financial risks of the traditional fishery sector, as they may compete for limited subsidy resources (Gibbs, 2004).

Wind and wave farms

The idea to combine new emerging industries, such as offshore wind farms and marine aquaculture, within the same ocean territory may provide an opportunity to create multi-purpose marine areas. Besides integrating conflicting demands, this might also yield substance for policy options and future strategies beyond the national level. Naturally, multiple uses are closely interconnected in that the activities of one group influence actions by other user groups. The interacting groups have to somehow cooperate with each other and find suitable management forms in order to avoid adverse impacts associated with the multiple-use counterpart. In natural resources management, negotiated agreements and other legal or informal arrangements between different groups and various levels of governments have attracted considerable attention as a management alternative that contributes to social and economic mainstay of sustainability. Some of the greatest benefits attributed to cooperative management are characterized as task allocation, resource exchange, linkage of different types and levels of organization, reduced transaction costs, risk sharing and conflict resolution.

Along coasts with plans or existing wind and wave farms, the observed high spatial competition of stakeholders has encouraged the idea of integrating open ocean aquaculture in conjunction with offshore wind farms beyond the 12 miles zone. The cultivation of seaweeds and blue mussels is biologically and technically feasible in a high-energy environment using modified cultivation strategies (Buck *et al.*, 2008). The point of departure of a proposed multi-use concept is that the solid groundings of wind turbines or wave farms can serve as attachment points for the aquaculture installations and become the key to the successful commercial cultivation of any offshore aquatic organism. However, spaces in between the turbines are also attractive for farming projects, since public access is restricted and thus, the cultivation site protected from outside influences. An economic analysis of different operation scenarios indicates that the market price, the annual settlement success of juvenile mussels and availability of food are the main factors that determine the breakeven point for mussel farming and as operational costs are for fish farming. Social and policy science research reveals that the integration of relevant actors into the development of a multi-use concept for wind/wave farms and aquaculture interaction is a complex and controversial issue (Buck *et al.*, 2008). Combining knowledge and experience of wind/wave farm planners, as well as mussel fishers and aquaculturists within the framework of national and international policies will be the most important component for designing and developing an effective offshore co-management regime to limit the consumption of ocean space.

Exploitation industries

The exploitation of oil, gas, sand, gravel and mining potentially interacts with offshore farming. For instance, the United Kingdom oil and gas exploitation activities take place in the North Sea, which is a potential site for offshore farming. However, as the actual space used by fish farms is relatively small, it should be possible to accommodate fish farming along with exploitation activities. As with the wind and wave farms there is a potential of sharing resources when combining exploitation and offshore farming, such as ships and landing facilities, which could be of mutual benefit for both users. Fish farming in connection with abandoned exploitation facilities (e.g. old oil rigs) has been proposed as a possible solution to solving some of the technological constrains of offshore farming and thus lowering the development costs of offshore farming. Regulation, as will be discussed below, is probably one of the most critical concerns to solve issues among multi-users of this zone. Fish farms have to be located at a safe distance from possible sources of contamination, such as oil spills and chemical hazards.

Maritime transport

Offshore farming interacts with the maritime transport for siting of farms. It is necessary to place the farms away from intensive shipping routes, such as the international traffic routes along coast lines and across oceans. There are certain areas with intense maritime transport such as the English Channel and Strait of Gibraltar, where establishment of offshore farms should be prohibited or strictly controlled. The actual area used by fish farms is small, and by proper planning of offshore siting, e.g. by confining the farms to certain zones of production activities, it should be possible to avoid conflicts with maritime transport. It is now possible to secure the farms through various remote alarm systems used in modern navigation, making the farms visible to the ships, independent of weather conditions, sight and wave activity. The most difficult conflicts are probably with active fishing fleets, and it can be argued that farms should be placed outside intensive fishing areas or in reserves within the fishing area. Specific interactions with fisheries have been discussed earlier in this review.

ECOSYSTEM ISSUES

Ecological foodprint (feed resources)

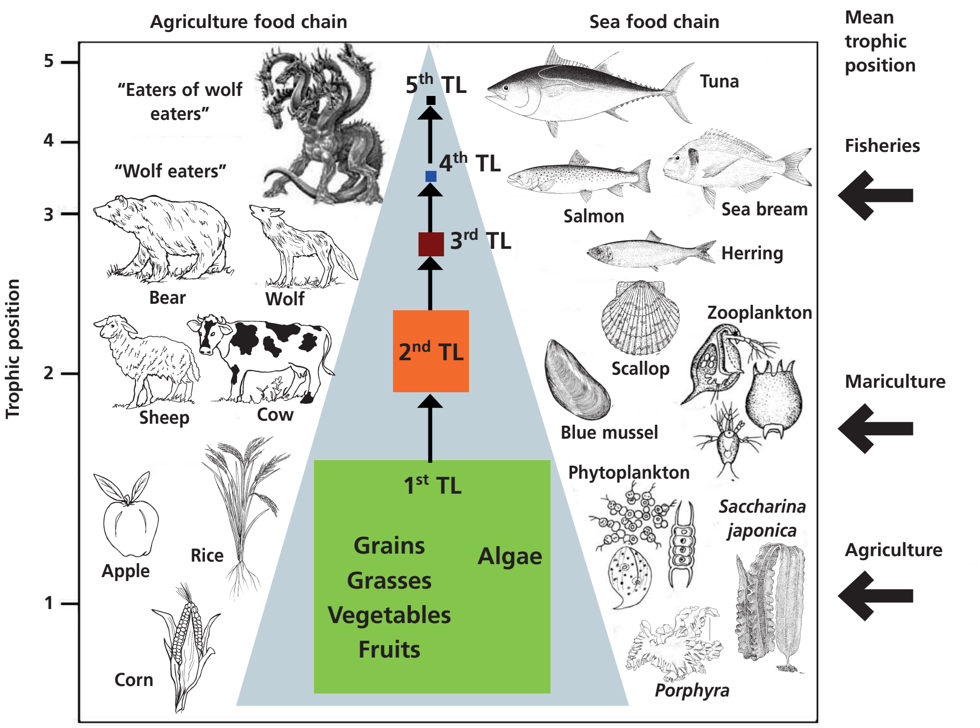
The feed resources used for off-the-coast and offshore farming are considered to be the same as in coastal aquaculture, undergoing the same development as in coastal aquaculture, where the feed is constantly modified for improving the economic output of farming (Asche, Roll and Tveteras, 2009). It is possible that offshore farming will require some optimization with respect to the physical conditions (e.g. sinking rates, breakage, conservation), but as the same species are considered to be cultured, the overall composition of the feed pellets is expected to be quite similar. The composition of feed pellets are currently developed to contain a larger fraction of terrestrial derived compounds to minimize the pressure on fish meal and in particular fish oil, which is near its exploitation limit (Duarte *et al*., 2009). At present, small pelagic forage fish species such as anchovies, herring, mackerel, sardines, etc., represent the largest landed species group in capture fisheries (27.3 million tonnes or 29.7 percent of total capture fisheries landings in 2006 (Tacon and Metian, 2009a; Tacon and Metian, 2009b). They also currently constitute the major species group actively fished and targeted for nonfood uses, including reduction into fishmeal and fish oil for use within compound animal feeds, or for direct animal feeding; the aquaculture sector alone consumed the equivalent of about 23.8 million tonnes of fish (live weight equivalent) or 87 percent in the form of feed inputs in 2006 (Tacon and Metian, 2008; Tacon and Metian, 2009a; Tacon and Metian, 2009b). The main pressure from development of off-the-coast and offshore farming is thus not specific demands, but more the quantity of fish feed expected to be used by the prospected increase in production volume (Duarte *et al.*, 2009). The efficiency of feed use in off-the-coast and offshore can be argued, some suggest at lower efficiency due to the larger loss under the more difficult production conditions (e.g. less precise feeding in larger farms, increased dispersion of fish feed), whereas others proposed more efficient feeding due to less disease and increased welfare for the fish in larger cages and higher water exchange rates in the cages. Various solutions to high ecological foodprints in fish farming have been proposed such as introducing integrated multitrophic farming (see below); change from marine to terrestrial sources of feed, using macroalgae or mussel meal instead of small fishes and lowering the trophic chain in aquaculture (Figure 3) (Duarte *et al.*, 2009).

Carbon footprint

Compared to most other animal husbandry practices, aquaculture has a small overall CO_2 carbon footprint (Bunting and Pretty, 2007). This is particularly the case for freshwater herbivorous or omnivorous species such as carp, requiring at most small amounts of fertilizer, often organic, and in some cases, low-energy supplementary

FIGURE 3

Comparison of trophic chains within the agriculture (left) and seafood chain (right). Currently mariculture has a trophic position of 1.7 due to intensive algae and shellfish culture in China, compared with 3.5 in salmon and seabream farming



Source: Modified from Duarte *et al.*, 2009.
Note: All line drawings by Manuela D'Antoni, FAO.

feeds, although high feed conversion rates (FCR) for some species such as tilapia has negative impact on the carbon footprint (Table 4). In contrast shrimp, salmon and marine carnivores, due to their high feed energy or system energy demands, have very high footprints. However, as farmed aquatic organisms do not themselves emit methane, such as observed for livestock, it reduces the total carbon footprint per tonne. Off-the-coast and offshore farming, compared to coastal farming, increase the carbon footprint due to the fuel costs for increased transportation of feed and fish. As in all food production sectors, post-harvest activities entail stocking, packaging and transporting and they create post-consumption waste, all linked with CO_2 emissions. In this case, off-the-coast and offshore production is not considered to differ from coastal farming. Of special note of CO_2 emissions are those related to air transport. Intercontinental

TABLE 4

Energy use in aquatic farming systems compared to agriculture

	Industrial energy consumption (GJ t^{-1})
Semi-intensive shrimp farming	169
Grouper, sea bass cages	95
Carp, intensive recycle	56
Salmon cages	56–105
Trout ponds	28
Catfish ponds	25
Carp ponds, feeding and fertilizer	11
Pork[1]	16
Beef[1]	40

[1] De Vries and de Boer (2010)

Source: Bunting and Pretty, 2007.

airfreight may emit 8.5 kg CO_2 per kg of fish shipped, about 3.5 times the levels from sea freight, and more than 90 times those from transport of fish consumed within 400 km of its source. Product form will also have an important effect, including energy embodied in packaging, and can influence options for maintaining quality and value with respect to transport method. As the same species are considered to be produced in off-the-coast and offshore farms, it is not likely that CO_2 emissions of post-harvest activities will change significantly. Tuna farming should be mentioned as a particular carbon costly production due to the use of air transportation of fresh fish.

Environmental costs

There are environmental costs associated with every form of food production, including aquaculture and none of these appear sustainable at the present time (Brooks, 2007). It has been obvious for several decades that the food resources in the oceans are being over-exploited and few jurisdictions have been successful in managing the harvest of fish and shellfish. Whereas small-scale aquaculture is an ancient practice, industrial-scale aquaculture is relatively new and because of its scale, it can potentially carry significant environmental costs which must be managed to ensure that they do not become widespread or irreversible.

As discussed in previous sections, environmental effects on water quality and pelagic food webs are considered to be less severe compared to the benthic environment. For coastal salmon aquaculture in the Northeast Pacific, Brooks (2007) found that significant effects on the benthic environment to be restricted to a few hectares within 200 m of net cages, which is consistent with findings for coastal aquaculture in general. He found, that biogeochemical remediation of the sediments at reasonably well sited farms took 6–12 months. In the worst case studied, biogeochemical remediation was nearly, but not totally, complete following five years in fallow. Biological remediation occurred within one year following completion of biogeochemical remediation. The measured reductions in the biomass of benthic invertebrates due to organic enrichment resulted in the loss of approximately 300 kg of wild fish during production of 2.5 million kg of Atlantic salmon, which can be considered a relatively minor impact. In contrast Diaz-Almela *et al.*, 2008, found loss of the sensitive seagrass *Posidonia oceanica* in the Mediterranean, which can be considered an almost irreversible change due to the slow recolonization potential (hundreds of years). Under off-the-coast and offshore conditions, organic enrichment is considered to be less, and if sensitive habitats are avoided, production could possibly proceed longer on a single site before fallowing is required to recover the sediments biogeochemically and biologically. On the other hand, biogeochemical and biological remediation may take longer at deeper sites, as discussed in previous chapters, and thus increasing the environmental costs. Compared to producing an equal amount of beef, the small (1.6 ha average) and short-lived (44 month-long) effects created by salmon farming, is negligible. For comparison production of equal amounts of beef requires 6 982 ha of high quality pasture for 30 months plus as long as several hundred to a thousand years of remediation. Brooks (2007) also concluded that for achieving sustainability it is necessary to prioritizing the costs of all forms of food production and focusing on solving the most important and tractable issues first. For instance, bycatch and lost fishing nets and pots waste a significant portion of the ocean resources each year. From a sustainability point of view, these costs represent a far greater hazard to marine life than the lost production under a salmon farm.

Carrying capacity

Carrying capacity of off-the-coast and offshore farming is considered to be higher due to the dispersion of particulate waste products minimizing the benthic impacts. It is, however, important to consider the lack of scientific evidence behind these expectations. Due to the lack of knowledge on impacts of organic enrichment in deep sediments, including studies of fallowing times required for re-establishment of the biogeochemical and faunal conditions in the sediments, it is difficult to predict carrying or assimilative capacities at offshore locations. There is a need of experimental studies and monitoring efforts under off-the-coast and offshore conditions along with modelling of organic enrichments, e.g. as done for coastal aquaculture, where several models of benthic impacts are available. As deep sediments are generally considered to be carbon limited, they are expected to be able to take up significant amounts of organic matter, but as this organic matter differs widely (e.g. amount and composition) from the organic matter usually settling in deep systems, both the biological and biogeochemical response of deep communities may turn out different than expected. Benthic communities, low in abundance, diversity and biomass, may be quite sensitive to organic enrichments, in particular if the organic matter load exceeds the capacity of the community to consume the organic matter (Gallucci *et al.*, 2008). In such a case, the microbial processes are stimulated, and potentially reducing the sediments and eliminating less pollutant tolerant species. It could well be a large fraction of the benthic fauna as they are adapted to carbon starved conditions rather than organic rich, anoxic and sulfidic sediments. It is likely the recovery of deep-sea habitats will occur, but it will probably take longer, especially as many deep-sea species have slower growth rates, later sexual maturation and variable or infrequent recruitment (Levin *et al.*, 2001).

REGULATION AND MONITORING

The legal and regulatory environment surrounding the offshore aquaculture industry is cited consistently as one of the major hurdles to its development (Fletcher, 2003). Individuals interested in developing sustainable offshore aquaculture face challenges in the form of a fragmented and often inconsistent permitting process among the international, national, and local agencies and questions regarding leasing, siting and property rights. The lack of adequate leasing options restricts the feasibility of moving farms offshore. One avenue to sustainable offshore aquaculture is the consolidation of specific sites for aquaculture leases. Marine zoning faces significant challenges that its land-based counterpart does not, such as boundary disputes, enforcement difficulties, and more frequent user conflicts. Coastal and offshore waters represent a public resource for use by fishers, recreationalists, mineral exploiters, and the shipping industry. Despite significant policy conflicts, coastal managers across the globe are recognizing the importance of setting aside particular areas of marine waters for specific uses. These include marine sanctuaries; areas used as military zones; specific lease areas for offshore oil and gas exploration; and, state and federal "marine reserves" or "marine protected areas" to conserve fish and other marine resources. There is still much to learn about the deep sea, making comparisons with existing coastal protected areas difficult. One suggested solution is the development of a marine reserve network extending throughout coastal areas and the high seas (Houde and Roberts, 2004). Networks of protected areas could protect highly migratory species, and may even protect undiscovered habitats such as those associated with seamounts. Another potential mechanism to protect migratory deep-sea species could be mobile reserves that would follow sensitive species along migration routes. In the deep sea, potentially the most immediately effective measure would be to allow aquaculture production in areas where fish stocks have reduced and benthic damage already occurred but to close other areas to new fishing to protect existing fish stocks and benthic habitats.

When farms have been established on off-the-coast or offshore locations, it is important to monitor the farms to follow-up on the environmental impacts. Monitoring of off-the-coast and offshore locations is constrained by the water depth and the high cost of operation under such conditions. Furthermore, the lack of scientific knowledge on possible impacts makes monitoring further cumbersome. Water quality parameters are possibly easier to follow, as there are already now various techniques for remote sensing of water column parameters (temperature, oxygen, nutrients, fluorescent), and loss of feed and faeces can be monitored by videography and deployment of sedimentation traps. The main problem is the benthic impacts, at potentially deep locations (50 to several hundred meters). Remotely operated vehicles (ROVs) can support collection of benthic samples by visually inspecting the sediment surface, but sampling has to be undertaken to study the organic enrichment and fauna communities. There is still a lack of consensus on monitoring of aquaculture farms in coastal areas (e.g. Borja *et al.*, 2009; Holmer *et al.*, 2008), and even less is known about the benthic response of off-the-coast and offshore locations. In the EU-funded Ecosystem Approach to Sustainable Aquaculture (ECASA) project, Borja *et al.* (2009) found that indices based on benthic fauna showed contradictory responses in several indicators (individual abundance, biomass), whereas a more consistent response was found when applying indices (Infaunal Trophic Index [ITI] and AZTI's Marine Biotic Index [AMBI]). They demonstrated that the environmental variables were explained by the variability in the macrofaunal variables (up to 53 percent), while the remaining variance was divided among three groups of variables: (i) hydrography (12 percent, depth, distance to farm, average current speed); (ii) sediment (5 percent, Eh and percentages of silt and total organic matter); and (iii) cages (15 percent, years of production and annual production). They suggested the use of several benthic indicators/indices in assessing farm impacts, together with the investigation of dynamics of the studied location (water depth, years of farm activity, total annual production), to be able to interpret the response of benthic communities to the organic enrichment from aquaculture. These suggestions are already much more detailed than undertaken at most coastal farms at present, and due to the larger area of dispersion of waste products at offshore farms, such analysis will be operationally demanding. Similar monitoring programmes, slightly less detailed, are already in use in Norway, Scotland and Canada. e.g. by using the Modelling-Ongrowing Fish Farms-Monitoring (MOM) protocol (Ervik *et al.*, 1997; Hansen *et al.*, 2001; Wildish, Hargrave and Pohle, 2001), and could be adapted for use in off-the-coast and offshore locations. Modelling of the dispersion could be a tool to focus the sampling efforts in spatial and temporal dimensions.

OTHER ISSUES

External factors

At the moment, climate change is actively working as an external forcing factor on marine aquaculture, as the suitable areas of farming are expanding into the Arctic due to reduced ice cover and increased production period during summer. Hardly any information is available on the fate of waste products under Arctic conditions. Both the pelagic and benthic communities are quite productive, when they are not limited by light or carbon input, and it is likely that they can accommodate inputs of dissolved nutrients and organic matter, but research should be done to explore the fate of waste products in the Arctic along with increasing temperatures and light availability. Climate change may also affect aquaculture production at lower latitudes, as the production season may be prolonged due to higher water temperatures during winter, which may increase the nutrient and organic load compared to existing conditions and affect the carrying capacity of sites. Carrying capacity is often based on an annual production following a seasonal growth pattern with low feeding during winter. Also, higher summer temperatures may affect aquaculture production, but more likely in a negative way, as for instance salmon and rainbow trout do not tolerate high temperatures well and decrease feeding during warm temperatures. Intensive weather events, such as increasing storm frequency and harmful algae blooms (HABs) may also negatively affect aquaculture production by increasing the risk of damage to the farm installation and reduced water quality in the farms leading to mass mortality.

Economy is an important driver of marine aquaculture and some will say the most important driver (Asche, Roll and Tveteras, 2008). Off-the-coast and offshore farming have been proposed now for many years, over a decade, and in particular offshore farming seems to develop slower than proposed. Investment costs and fluctuating market sales are some of the drivers of offshore aquaculture production. The environmental pressure on offshore locations will depend on the degree of expansion into the offshore zones and the need to consider only a few farms or like in Norway >50 percent of the aquaculture production as off-the-coast/offshore. The investment costs are likely to decrease as the sector expands, whereas operational costs may be constant or even increase due to increased price for feed, labour and energy use. The market situation is strongly dependent on the public perception to fish products and aquaculture production, but as the capture fisheries will not be able to feed a growing human population, it is likely that the demand for healthy seafood to the wealthier part of the world will increase significantly in the near future. At present, the economic crisis of the Western world has decreased the demand for seafood, and it is only due to the collapse of salmon production in Chile, that the price is kept high for farmed salmon. Prices on seabream and seabass have also declined.

Integrated multi-trophic aquaculture

Ecologically friendly aquaculture crops, such as seaweeds, herbivores, omnivores, and detritivores can be cultured using relatively less of our limited natural resources and produce relatively less pollution (Neori, 2008). They also top FAO's estimates of aquaculture crops for the 21st century. These crops already comprise nearly 90 percent of global aquaculture tonnage, >90 percent of all aquaculture production in China and >60 percent of production even in North America. Consumers prefer them, most likely due to their low prices. It is therefore important to consider these principles also in off-the-coast and offshore aquaculture. It has been proposed that current monoculture practices and perceptions intrinsic to the aquaculture industry can be turned around into a sustainable profitable expansion of carnivores production with organisms lower in the food web in ecologically-balanced aquaculture farms (Duarte *et al*., 2009). Both blue mussels (*Mytilus edulis*) and macroalgae (brown seaweeds) have shown potentials when tested in the North Sea (Buck *et al*., 2008) but food availability for the mussels and physical conditions for both types of organisms need to be considered for each specific site. Species should be selected based on their ecological functions in addition to their economic potential under off-the-coast and offshore conditions. Particularly, the "cleaning aspect" of integrated multi-trophic aquaculture (IMTA) has to be considered, as waste products are dispersed rapidly and the filter effect by mussels may be constrained under offshore conditions. Low concentrations of "natural food" in the form of dissolved nutrients for macroalgae and phytoplankton for suspension feeding mussels have to be considered, as the growth rates may be too low to obtain an economically efficient production. Growth experiments with *M. edulis* in an offshore setting with high currents show that the mussels stay closed during strong current, limiting their growth rates at the low food availability (H.U. Risgaard, personal communication, 2010). Also growth of the brown macroalgae *Saccharina saccharias* was nutrient limited and had suboptimal growth rates for a significant part of the growth season (M. Birkeland, personal communication, 2010). Molluscs and seaweed farming has been proposed together with wind and wave farms, where they can benefit from existing structures and possible shelter as discussed in a previous chapter. The experience with an offshore aquaculture farm of *Laminaria saccharina* conducted in 2002 assessed the maximum hydrodynamic forces affecting farmed algae (Buck and Buchholz, 2005). The researchers tested *Laminaria* in tanks and found that neither did measured nor calculated values of drag exceed those forces of wind or current, provided the algae had been gown in a current >1 m s^{-1}. Even in storm conditions with maximum current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m can cultivated *L. saccharina* withstand the high energy environment.

Furthermore it is important to mention that governments have the tools to reward IMTA principles by means of tax credits and nutrient credits and to penalize unbalanced monoculture approaches by means of "polluter pays" fines, thereby providing IMTA farms with a significant economic advantage. Such measures are under investigation in several countries, and already in use for agriculture purposes in Sweden, where mussel cultures remove diffuse load of nitrogen from agriculture production (Lindahl *et al.*, 2005).

Research and development needs

As the knowledge about environmental interactions is very limited for the off-the-coast and offshore farms there are large research and development (R&D) needs within this field. This is particularly the case for the benthic effects due to organic enrichment, as the few studies available indicate organic enrichment also at off-the-coast and offshore farms. Studies are also needed for the water column, where there is little knowledge about effects of released dissolved nutrients and organic compounds under more oligotrophic conditions compared to coastal locations. Since environmental interactions depend on the farm production, such as size, species, location and feeding techniques, it is important to link surveys of environmental conditions at existing farms with experimental studies to clarify existing combinations of production and environmental conditions. In addition, numerous other factors such as the importance of attracted fish around the cages and their modification of environmental effects, the use of chemicals and medicines and their distribution in the environment, the risk of escapees, should be considered as R&D needs.

With respect to the discharge of nutrients to the water column, it is important to investigate their fate in the environment, especially in periods when production is not limited by light. There is a possibility that nutrients are transported up the food chain and contribute to changes in trophic relationships. Release of dissolved organic matter may stimulate bacterial production, and the fate of this pool of organic matter may be relevant to both the oxygen conditions in the water column and the regeneration of nutrients and coupling to higher trophic levels.

In the benthic environment a key element to consider is the carrying capacity of the sediments and how will it be affected by the addition of organic matter of a different quality and quantity compared to natural systems. Knowledge of benthic fauna response to organic enrichment is not known as well as the restoration of fauna community after a possible modification due to organic enrichment. This has implications for fallowing principles. Also sensitive benthic communities and their response to organic enrichment are largely unknown.

For both off-the-coast and offshore farms there are a number of new production methods intended to be used. One example is submerged cages, which are lowered below the wave depth and thus are closer to the sea bottom. Due to the challenges of anchoring at large depths, floating net cage systems are tested, which can reduce the overall loading of waste products at a specific site, but spread the waste products over larger areas. Finally, farms located along with other types of farms (wind/wave) are also new with many new types of interactions, which can be envisaged.

Hydrodynamics are expected to differ much in off-the-coast and offshore farms. Basically the farms are more exposed and a larger dispersion of waste products, which may make it difficult to monitor farms in a controlled manner. Furthermore, complex coastal and ocean currents, and their variations over seasons lead to complex situations. Stratification of water masses and tidal effects can also contribute to complex sedimentation conditions, which makes it difficult to examine both near-field as far-field effects.

An important environmental aspect of the off-the-coast and offshore farms is locating far from land, increasing the energy consumption for maintenance due to increased transport. It is, therefore, essential to develop alternative energy supplies for farms, for example in the form of wind, wave and solar power to supplement the farms with energy and reducing carbon footprint.

IMTA principles are well established in many tropical fish farming systems, but are still in their infancy in coastal aquaculture, and limited experience is available for off-the-coast and offshore farms. It is therefore necessary to explore first the environmental impacts of IMTA and analyze the environmental benefits. Specifically, it is necessary to examine how coupling between different trophic levels and sufficient high growth rates can be achieved under the often more nutrient-poor conditions under off-the-coast and offshore conditions. Also it will be important to understand the fate of waste products in the Arctic and Antarctic during a climate change scenario, as well as interactive impacts of nutrient and organic matter loading of pelagic and benthic systems along with increases in temperature and light availability.

There is an urgent need for a consensus around the monitoring of marine aquaculture worldwide. Several of the major producer countries apply fairly comprehensive monitoring programmes, whereas monitoring is more sporadic in many other countries. There is a need for a proliferation of existing knowledge from the well-established programmes, as well as an adaptation to new conditions for the off-the-coast and offshore conditions. This is particularly true with respect to the use of larger farms, the significance of an increased water column and deeper sediments. Monitoring programmes must be adapted in terms of spatial and temporal scales, and development of remote sensing equipment (e.g. loggers, surveillance cameras) and monitoring equipment for deep water (e.g. ROV) is required.

Mapping of habitat and hydrodynamics. It is necessary to get a much better understanding of benthic communities at the proposed sites. The benthic habitats are poorly described specifically for offshore sites, where there is limited knowledge on the distribution of sensitive habitats such as maerl, sponge and cold water corals. As hydrodynamics are considered so important for off-the-coast and offshore conditions, it is important to have good description of local hydrodynamic conditions which may affect the farming conditions.

CONCLUSION

Based on this review, the predictions for environmental interactions of offshore compared to off-the-coast farming are summarized in Table 5. The most important interactions in offshore are those related with visual impacts, benthic flora, wild fish and use of fish as feed. Of these four issues, the visual impacts and negative impacts on benthic flora are expected to disappear by moving offshore. Interactions with wild fish are expected to be reduced, whereas the use of fish in feed will remain unchanged. Similarly most other interactions are expected to be reduced or remain unchanged by moving the farms offshore, and as such environmental benefits can be expected. This is particularly the case, if farms are placed at locations with high degree of exposure and erosion bottoms, increasing dispersal beyond the biological response time for uptake of waste particles.

Major gaps of knowledge are related to mapping of the deep seafloor and sensitive habitats. Experimental evidence of organic matter enrichment is needed to understand the assimilative capacity of deep sea sediments, as well as the response of the infauna to fallowing. Finally, relations between cultured and wild fish with respect to genetic, disease and parasitic interactions need further examination before farming offshore can be recommended.

TABLE 5

Environmental impacts of mariculture in off-the-coast locations and predictions for offshore locations. Impacts are categorized as "low" (barely detectable), "medium" (enrichment/ detectable), "severe" (negative impact) and predictions at offshore as "lower", "no change" or "higher" impact compared to off-the-coast

Impact	Observed off-the-coast	Prediction offshore
Water quality (nutrients)	Low	Lower
Carbon footprint	Low	Higher
Enrichment sediments	Medium	Lower
Sediment microbial activity	Medium	Lower
Invasion of exotic species	Medium	Lower
Wild fish (disease)	Medium	Lower/no change
Benthic fauna	Medium	Lower/no change/higher
Wild fish (attraction)	Medium	No change
Fisheries	Medium	No change
Use of antifoulants/chemicals	Medium	No change/higher
Escapees (incl. spawning)	Medium	No change/higher
Visual impacts	Severe	Lower
Benthic flora	Severe	Lower
Wild fish (genetics)	Severe (salmon)	Lower/no change
Use of fish as feed	Severe	No change

REFERENCES

Aguado-Gimenez, F., Marin, A., Montoya, S., Marin-Guirao, L., Piedecausa, A. & Garcia-Garcia, B. 2007. Comparison between some procedures for monitoring offshore cage culture in western Mediterranean Sea: Sampling methods and impact indicators in soft substrata. *Aquaculture*, 271: 357–370.

Apostolaki, E.T., Tsagaraki, T., Tsapaki, M. & Karakassis, I. 2007. Fish farming impact on sediments and macrofauna associated with seagrass meadows in the Mediterranean. *Estuarine Coastal and Shelf Science*, 75: 408–416.

Asche F., Roll, K.H. & Tveteras, R. 2008. Future trends in aquaculture: Productivity growth and increased production. *In* M. Holmer, K. Black, C.M., Duarte, N. Marba & I. Karakassis, eds. *Aquaculture in the Ecosystem*, 271–292. Springer.

Asche, F., Roll, K.H. & Tveteras, R. 2009. Economic inefficiency and environmental impact: An application to aquaculture production. *Journal of Environmental Economics and Management*, 58: 93–105.

Asche, F. & Tveteras, S. 2004. On the relationship between aquaculture and reduction fisheries. *Journal of Agricultural Economics*, 55: 245–265.

Avendano-Herrera, R., Nunez, S., Barja, J.L. & Toranzo, A.E. 2008. Evolution of drug resistance and minimum inhibitory concentration to enrofloxacin in Tenacibaculum maritimum strains isolated in fish farms. *Aquaculture International*, 16: 1–11.

Basaran, A.K., Aksu, M. & Egemen, O. 2007. Monitoring the impacts of the offshore cage fish farm on water quality located in Ildir Bay (Izmir-Aegean Sea). *Tarim Bilimleri Dergisi-Journal of Agricultural Sciences*, 13: 22–28.

Beveridge, M.C.M., Phillips, M.J. & Macintosh, D.J. 1997. Aquaculture and the environment: the supply of and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. *Aquaculture Research*, 28: 797–807.

Bjorn, P.A. & Finstad, B. 2002. Salmon lice, *Lepeophtheirus salmonis* (Kroyer), infestation in sympatric populations of Arctic char, *Salvelinus alpinus* (L.), and sea trout, *Salmo trutta* (L.), in areas near and distant from salmon farms. *Ices Journal of Marine Science*, 59: 131–139.

Bjorn, P.A., Finstad, B., Kristoffersen, R., McKinley, R.S. & Rikardsen, A.H. 2007. Differences in risks and consequences of salmon louse, *Lepeophtheirus salmonis* (Kroyer), infestation on sympatric populations of Atlantic salmon, brown trout, and Arctic charr within northern fjords. *Ices Journal of Marine Science*, 64: 386–393.

Borja, A., Rodriguez, J.G., Black, K., Bodoy, A., Emblow, C., Fernandes, T.F., Forte, J., Karakassis, I., Muxika, I., Nickell, T.D., Papageorgiou, N., Pranovi, F., Sevastou, K., Tomassetti, P. & Angel, D. 2009. Assessing the suitability of a range of benthic indices in the evaluation of environmental impact of fin and shellfish aquaculture located in sites across Europe. *Aquaculture,* 293: 231–240.

Boyd, C.E., McNevin, A.A., Clay, J. & Johnson, H.M. 2005. Certification issues for some common aquaculture species. *Reviews in Fisheries Science,* 13: 231–279.

Boyra, A., Sanchez-Jerez, P., Tuya, F., Espino, F. & Haroun, R. 2004. Attraction of wild coastal fishes to an Atlantic subtropical cage fish farms, Gran Canaria, Canary Islands. *Environmental Biology of Fishes,* 70: 393–401.

Braithwaite, R.A., Carrascosa, M.C.C. & Mcevoy, L.A. 2007. Biofouling of salmon cage netting and the efficacy of a typical copper-based antifoulant. *Aquaculture,* 262: 219–226.

Brehmer, P., Gerlotto, F., Guillard, J., Sanguinede, F., Guennegan, Y. & Buestel, D. 2003. New applications of hydroacoustic methods for monitoring shallow water aquatic ecosystems: the case of mussel culture grounds. *Aquatic Living Resources,* 16: 333–338.

Brooks, K.M. 2007. Assessing the environmental costs of Atlantic salmon cage culture in the Northeast Pacific in perspective with the costs associated with other forms of food production. *In* D.M. Bartley, C. Brugère, D. Soto, P. Gerber & B. Harvey, eds. *Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons.* FAO/WFT Expert Workshop. 24–28 April 2006, Vancouver, Canada. FAO Fisheries Proceedings No.10.Rome, FAO.2007. 241 pp.

Buck, B.H. & Buchholz, C.M. 2005. Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. *Aquaculture,* 250: 674–691.

Buck, B.H., Krause, G., Michler-Cieluch, T., Brenner, M., Buchholz, C.M., Busch, J.A., Fisch, R., Geisen, M. & Zielinski, O. 2008. Meeting the quest for spatial efficiency: progress and prospects of extensive aquaculture within offshore wind farms. *Helgoland Marine Research*, 62: 269–281.

Buck, B.H., Thieltges, D.W., Walter, U., Nehls, G. & Rosenthal, H. 2005. Inshore-offshore comparison of parasite infestation in *Mytilus edulis*: implications for open ocean aquaculture. *Journal of Applied Ichthyology,* 21: 107–113.

Bunting, S.W. & Pretty, J. 2007. *Aquaculture development and global carbon budgets: Emissions, sequestration and managment options*. Centre for Environment and Society Occasional Paper 2007–1.University of Essex, United Kingdom. 2007.

Carney, R.S. 2005. *Zonation of deep biota on continental margins*. CRC Press-Taylor & Francis Group, Boca Raton.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C. & Likens, G.E. 2009. Eutrophication: Time to adjust expectations response. *Science*, 324: 724–725.

Costello, M.J., Grant, A., Davies, I.M., Cecchini, V., Papoutsoglou, S., Quigley, D. & Saroglia, M. 2001. The control of chemicals used in aquaculture in Europe. *Journal of Applied Ichthyology*, 17: 173–180.

Cranford, P.J., Hargrave, B.T. & Doucette, L.I. 2009. Benthic organic enrichment from suspended mussel (*Mytilus edulis*) culture in Prince Edward Island, Canada. *Aquaculture*, 292: 189–196.

Cromey, C.J., Nickell, T.D. & Black, K.D. 2002. DEPOMOD – modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture*, 214: 211–239.

Cross, T., Burnell, G., Coughlan, S., Culloty, S., Dillance, E., McGinnity, P. & Rogan, E. 2008. Detrimental genetic effects of interactions between reared strains and wild populations of marine and anadromous fish and invertebrate species. *In* M. Holmer, K. Black, C.M., Duarte, N. Marba & I. Karakassis, eds. *Aquaculture in the Ecosystem*, 117–154. Springer.

Dalsgaard, T. & Krause-Jensen, D. 2006. Monitoring nutrient release from fish farms with macroalgal and phytoplankton bioassays. *Aquaculture*, 256: 302–310.

Dandonneau, Y., Deschamps, P.Y., Nicolas, J.M., Loisel, H., Blanchot, J., Montel, Y., Thieuleux, F. & Becu, G. 2004. Seasonal and interannual variability of ocean color and composition of phytoplankton communities in the North Atlantic, equatorial Pacific and South Pacific. *Deep-Sea Research Part II – Topical Studies in Oceanography*, 51: 303–318.

De Vries, M. & de Boer, I.J.M. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science,* 128: 1–11.

Dean, R.J., Shimmield, T.M. & Black, K.D. 2007. Copper, zinc and cadmium in marine cage fish farm sediments: An extensive survey. *Environmental Pollution*, 145: 84–95.

Dempster, T., Fernandez-Jover, D., Sanchez-Jerez, P., Tuya, F., Bayle-Sempere, J., Boyra, A. & Haroun, R.J. 2005. Vertical variability of wild fish assemblages around sea-cage fish farms: implications for management. *Marine Ecology – Progress Series,* 304: 15–29.

Dempster, T., Sanchez-Jerez, P., Bayle-Sempere, J. & Kingsford, M. 2004. Extensive aggregations of wild fish at coastal sea-cage fish farms. *Hydrobiologia,* 525: 245–248.

Dempster, T., Sanchez-Jerez, P., Bayle-Sempere, J.T., Gimenez-Casalduero, F. & Valle, C. 2002. Attraction of wild fish to sea-cage fish farms in the south-western Mediterranean Sea: spatial and short-term temporal variability. *Marine Ecology – Progress Series,* 242: 237–252.

Dempster, T., Uglem, I., Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J., Nilsen, R. & Bjorn, P.A. 2009. Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. *Marine Ecology – Progress Series,* 385: 1–14.

Diaz, R.J. & Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. *Science,* 321: 926–929.

Diaz-Almela, E., Marba, N., Alvarez, E., Santiago, R., Holmer, M., Grau, A., Mirto, S., Danovaro, R., Petrou, A., Argyrou, M., Karakassis, I. & Duarte, C.M. 2008. Benthic input rates predict seagrass (*Posidonia oceanica*) fish farm-induced decline. *Marine Pollution Bulletin*, 56: 1332–1342.

Dimitriou, E., Katselis, G., Moutopoulos, D.K., Akovitiotis, C. & Koutsikopoulos, C. 2007. Possible influence of reared gilthead sea bream (*Sparus aurata*, L.) on wild stocks in the area of the Messolonghi lagoon (Ionian Sea, Greece). *Aquaculture Research,* 38: 398–408.

Dolan, M.F.J., Grehan, A.J., Guinan, J.C. & Brown, C. 2008. Modelling the local distribution of cold-water corals in relation to bathymetric variables: Adding spatial context to deep-sea video data. *Deep Sea Research Part I – Oceanographic Research Papers,* 55: 1564–1579.

Dominguez, L.M., Calero, G.L., Martin, J.M.V. & Robaina, L.R. 2001. A comparative study of sediments under a marine cage farm at Gran Canaria Island (Spain). Preliminary results. *Aquaculture,* 192: 225–231.

Douvere, F. & Ehler, C.N. 2009. New perspectives on sea use management: Initial findings from European experience with marine spatial planning. *Journal of Environmental Management,* 90: 77–88.

Duarte, C.M., Holmer, M., Olsen, Y., Soto, D., Marba, N., Guiu, J., Black, K. & Karakassis, I. 2009. Will the oceans help feed humanity? *Bioscience,* 59: 967–976.

Eriksson, S.P. & Baden, S.P. 1997. Behaviour and tolerance to hypoxia in juvenile Norway lobster (*Nephrops norvegicus*) of different ages. *Marine Biology,* 128: 49–54.

Ervik, A., Hansen, P.K., Aure, J., Stigebrandt, A., Johannessen, P. & Jahnsen, T. 1997. Regulating the local environmental impact of intensive marine fish farming – I. The concept of the MOM system (Modelling Ongrowing fish farms Monitoring). *Aquaculture,* 158: 85–94.

Fernandez-Jover, D., Sanchez-Jerez, P., Bayle-Sempere, J., Carratala, A. & Leon, V.M. 2007. Addition of dissolved nitrogen and dissolved organic carbon from wild fish faeces and food around Mediterranean fish farms: Implications for waste-dispersal models. *Journal of Experimental Marine Biology and Ecology,* 340: 160–168.

Findlay, R.H. & Watling, L. 1997. Prediction of benthic impact for salmon net-pens based on the balance of benthic oxygen supply and demand. *Marine Ecology – Progress Series,* 155: 147–157.

Finstad, B., Bjorn, P.A., Grimnes, A. & Hvidsten, N.A. 2000. Laboratory and field investigations of salmon lice [*Lepeophtheirus salmonis* (Kroyer)] infestation on Atlantic salmon (*Salmo salar* L.) post-smolts. *Aquaculture Research,* 31: 795–803.

Fiske, P., Lund, R.A. & Hansen, L.P. 2006. Relationships between the frequency of farmed Atlantic salmon, *Salmo salar* L., in wild salmon populations and fish farming activity in Norway, 1989–2004. *Ices Journal of Marine Science,* 63: 1182–1189.

Fletcher, K.M. 2003. Marine aquaculture zoning: A sustainable approach in the growth of offshore aquaculture. *In* C.J. Bridger & B.A. Costa-Pierce, eds. *Open Ocean Aquaculture: From Research to Commercial Reality*, pp. 15–22. The World Aquaculture Society, Baton Rouge, Louisiana, United States of America.

Ford, J.S. & Myers, R.A. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. *Plos Biology,* 6: 411–417.

Gallucci, F., Moens, T., Vanreusel, A. & Fonseca, G. 2008. Active colonisation of disturbed sediments by deep-sea nematodes: evidence for the patch mosaic model. *Marine Ecology – Progress Series,* 367: 173–183.

Gibbs, M.T. 2004. Interactions between bivalve shellfish farms and fishery resources. *Aquaculture,* 240: 267–296.

Gray, J.S., Wu, R.S.S. & Or, V. 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. *Marine Ecology – Progress Series,* 238: 249–279.

Greene, J.K. & Grizzle, R.E. 2007. Successional development of fouling communities on open ocean aquaculture fish cages in the western Gulf of Maine, USA. *Aquaculture,* 262: 289–301.

Grizzle, R.E., Ward, L.G., Langan, V, Schnaittacher, G.M., Dijkstra, J.A. & Adams, J.R. 2003. Environmental monitoring at an open ocean aquaculture site in the Gulf of Maine: Results for 1997–2000. *In* C.J. Bridger & B.A. Costa-Pierce, eds. *Open Ocean Aquaculture: From Research to Commercial Reality*, pp. 105–117. The World Aquaculture Society, Baton Rouge, Louisiana, United States of America.

Gross, M.R. 1998. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. *Canadian Journal of Fisheries and Aquatic Sciences,* 55: 131–144.

Haedrich, R.L., Merrett, N.R. & O'Dea, N.R. 2001. Can ecological knowledge catch up with deep-water fishing? A North Atlantic perspective. *Fisheries Research,* 51: 113–122.

Hall-Spencer, J., White, N., Gillespie, E., Gillham, K. & Foggo, A. 2006. Impact of fish farms on maerl beds in strongly tidal areas. *Marine Ecology-Progress Series,* 326: 1–9.

Hansen, L.P. 2006. Migration and survival of farmed Atlantic salmon (*Salmo salar* L.) released from two Norwegian fish farms. *Ices Journal of Marine Science,* 63: 1211–1217.

Hansen, P.K., Ervik, A., Schaanning, V., Johannessen, V., Aure, V., Jahnsen, V. & Stigebrandt, A. 2001. Regulating the local environmental impact of intensive, marine fish farming II. The monitoring programme of the MOM system (Modelling-Ongrowing fish farms-Monitoring). *Aquaculture,* 194: 75–92.

Hargrave, B.T., Holmer, M. & Newcombe, C.P. 2008. Towards a classification of organic enrichment in marine sediments based on biogeochemical indicators. *Marine Pollution Bulletin,* 56: 810–824.

Havskum, H., Thingstad, T.F., Scharek, R., Peters, F., Berdalet, E., Sala, M.M., Alcaraz, M., Bangsholt, J.C., Zweifel, U.L., Hagstrom, A., Perez, M. & Dolan, J.R. 2003. Silicate and labile DOC interfere in structuring the microbial food web via algal-bacterial competition for mineral nutrients: Results of a mesocosm experiment. *Limnology and Oceanography,* 48: 129–140.

Heilskov, A.C., Alperin, M. & Holmer, M. 2006. Benthic fauna bio-irrigation effects on nutrient regeneration in fish farm sediments. *Journal of Experimental Marine Biology and Ecology,* 339: 204–225.

Heilskov, A.C. & Holmer, M. 2003. Influence of benthic fauna on organic matter decomposition in organic-enriched fish farm sediments. *Vie et Milieu-Life and Environment,* 53: 153–161.

Hodson, S.L., Burke, C.M. & Bissett, A.P. 2000. Biofouling of fish-cage netting: the efficacy of a silicone coating and the effect of netting colour. *Aquaculture,* 184: 277–290.

Hodson, S.L., Lewis, T.E. & Burke, C.M. 1997. Biofouling of fish-cage netting: Efficacy and problems of in situ cleaning. *Aquaculture*, 152: 77–90.

Holmer, M., Hansen, P.K., Karakassis, I., Borg, J.A. & Schembri, P.J. Monitoring of Environmental Impacts of Marine Aquaculture. *In* M. Holmer, K. Black, C.M. Duarte, N. Marba & I. Karakassis, eds. *Aquaculture in the Ecosystem*, 47–86. Springer.

Holmer, M. & Frederiksen, M.S. 2007. Stimulation of sulfate reduction rates in Mediterranean fish farm sediments inhabited by the seagrass *Posidonia oceanica*. *Biogeochemistry*, 85: 169–184.

Holmer, M. & Kristensen, E. 1994. Coexistence of sulfate reduction and methane production in an organic-rich sediment. *Marine Ecology – Progress Series,* 107: 177–184.

Holmer, M., Marba, N., Diaz-Almela, E., Duarte, C.M., Tsapakis, M. & Danovaro, R. 2007. Sedimentation of organic matter from fish farms in oligotrophic Mediterranean assessed through bulk and stable isotope (delta C-13 and delta N-15) analyses. *Aquaculture,* 262: 268–280.

Holmer, M., Perez, M. & Duarte, C.M. 2003. Benthic primary producers – a neglected environmental problem in Mediterranean maricultures? *Marine Pollution Bulletin,* 46: 1372–1376.

Houde, E.D. & Roberts, S.J. 2004. Marine protected areas: An old tool for new circumstances. *Aquatic Protected Areas As Fisheries Management Tools,* 42: 23–35.

Hughes, D.J. & Gage, J.D. 2004. Benthic metazoan biomass, community structure and bioturbation at three contrasting deep-water sites on the northwest European continental margin. *Progress in Oceanography,* 63: 29–55.

Kapetsky, J.M., Aguilar-Manjarrez, J. & Jenness, J. 2012. *A spatial assessment of potential for offshore mariculture development from a global perspective*. FAO Fisheries and Aquaculture Technical Paper No. 549. Rome, FAO.

Klitgaard, A.B. & Tendal, O.S. 2004. Distribution and species composition of mass occurrences of large-sized sponges in the northeast Atlantic. *Progress in Oceanography,* 61: 57–98.

Krkosek, M., Gottesfeld, A., Proctor, B., Rolston, D., Carr-Harris, C. & Lewis, M.A. 2007. Effects of host migration, diversity and aquaculture on sea lice threats to Pacific salmon populations. *Proceedings of the Royal Society B-Biological Sciences,* 274: 3141–3149.

Krkosek, M., Morton, A., Volpe, J.P. & Lewis, M.A. 2009. Sea lice and salmon population dynamics: effects of exposure time for migratory fish. *Proceedings of the Royal Society B-Biological Sciences,* 276: 2819–2828.

Kutti, T., Ervik, A. & Hansen, P.K. 2007a. Effects of organic effluents from a salmon farm on a fjord system. I. Vertical export and dispersal processes. *Aquaculture,* 262: 367–381.

Kutti, T., Ervik, A. & Hoisaeter, T. 2008. Effects of organic effluents from a salmon farm on a fjord system. III. Linking deposition rates of organic matter and benthic productivity. *Aquaculture,* 282: 47–53.

Kutti, T., Hansen, P.K., Ervik, A., Hoisaeter, T. & Johannessen, P. 2007b. Effects of organic effluents from a salmon farm on a fjord system. II. Temporal and spatial patterns in infauna community composition. *Aquaculture,* 262: 355–366.

Langhamer, O., Wilhelmsson, D. & Engstrom, J. 2009. Artificial reef effect and fouling impacts on offshore wave power foundations and buoys – a pilot study. *Estuarine Coastal and Shelf Science,* 82: 426–432.

Levin, L.A., Etter, R.J., Rex, M.A., Gooday, A.J., Smith, C.R., Pineda, J., Stuart, C.T., Hessler, R.R. & Pawson, D. 2001. Environmental influences on regional deep-sea species diversity. *Annual Review of Ecology and Systematics,* 32: 51–93.

Lin, D.T. & Bailey-Brock, J.H. 2008. Partial recovery of infaunal communities during a fallow period at an open-ocean aquaculture. *Marine Ecology – Progress Series,* 371: 65–72.

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.O., Olrog, L., Rehnstam-Holm, A.S., Svensson, J., Svensson, S. & Syversen, U. 2005. Improving marine water quality by mussel farming: A profitable solution for Swedish society. *Ambio,* 34: 131–138.

Machias, A., Karakassis, I., Giannoulaki, M., Papadopoulou, K.N., Smith, C.J. & Somarakis, S. 2005. Response of demersal fish communities to the presence of fish farms. *Marine Ecology – Progress Series,* 288: 241–250.

Macleod, C.K., Moltschaniwskyj, N.A. & Crawford, C.M. 2006. Evaluation of short-term fallowing as a strategy for the management of recurring organic enrichment under salmon cages. *Marine Pollution Bulletin,* 52: 1458–1466.

Macleod, C.K., Moltschaniwskyj, N.A. & Crawford, C.M. 2008. Ecological and functional changes associated with long-term recovery from organic enrichment. *Marine Ecology – Progress Series,* 365: 17–24.

Macleod, C.K., Moltschaniwskyj, N.A., Crawford, C.M. & Forbes, S.E. 2007. Biological recovery from organic enrichment: some systems cope better than others. *Marine Ecology – Progress Series,* 342: 41–53.

Magill, S.H., Thetmeyer, H. & Cromey, C.J. 2006. Settling velocity of faecal pellets of gilthead sea bream (*Sparus aurata* L.) and sea bass (*Dicentrarchus labrax* L.) and sensitivity analysis using measured data in a deposition model. *Aquaculture,* 251: 295–305.

Maldonado, M., Carmona, M.C., Echeverria, Y. & Riesgo, A. 2005. The environmental impact of Mediterranean cage fish farms at semi-exposed locations: does it need a re-assessment? *Helgoland Marine Research,* 59: 121–135.

Marin, S.L., Carvajal, J., Manriquez, A. & Mancilla, M. 2009. Effects of experimental infection by *Caligus rogercresseyi* (Copepoda: Caligidae) on the common jollytail, *Galaxias maculatus* (Osmeriforme: Galaxiidae) (Jenyns, 1842) in Chile. *Aquaculture,* 295: 138–141.

Matijevic, S., Kuspilic, G. & Baric, A. 2006. Impact of a fish farm on physical and chemical properties of sediment and water column in the middle Adriatic Sea. *Fresenius Environmental Bulletin,* 15: 1058–1063.

Mayor, D.J., Solan, M., Martinez, I., Murray, L., McMillan, H., Paton, G.I. & Killham, K. 2008. Acute toxicity of some treatments commonly used by the salmonid aquaculture industry to *Corophium volutator* and *Hediste diversicolor*: Whole sediment bioassay tests. *Aquaculture,* 285: 102–108.

Mayor, D.J., Solan, M., McMillan, H., Killham, K. & Paton, G.I. 2009. Effects of copper and the sea lice treatment Slice (R) on nutrient release from marine sediments. *Marine Pollution Bulletin,* 58: 552–558.

McAndrew, P.M., Bjorkman, K.M., Church, M.J., Morris, P.J., Jachowski, N., Williams, P.J.L. & Karl, D.M. 2007. Metabolic response of oligotrophic plankton communities to deep water nutrient enrichment. *Marine Ecology – Progress Series,* 332: 63–75.

McGinnity, P., Prodohl, P., Ferguson, K., Hynes, R., O'Maoileidigh, N., Baker, N., Cotter, D., O'Hea, B., Cooke, D., Rogan, G., Taggart, J. & Cross, T. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London Series B-Biological Sciences,* 270: 2443–2450.

McGinnity, P., Prodohl, P., Maoileidigh, N.O., Hynes, R., Cotter, D., Baker, N., O'Hea, B. & Ferguson, A. 2004. Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. *Journal of Fish Biology,* 65: 173–187.

Navarro, N., Leakey, R.J.G. & Black, K.D. 2008. Effect of salmon cage aquaculture on the pelagic environment of temperate coastal waters: seasonal changes in nutrients and microbial community. *Marine Ecology – Progress Series,* 361: 47–58.

Nelson, W.A. 2009. Calcified macroalgae – critical to coastal ecosystems and vulnerable to change: a review. *Marine and Freshwater Research,* 60: 787–801.

Neori, A. 2008. Essential role of seaweed cultivation in integrated multi-trophic aquaculture farms for global expansion of mariculture: an analysis. *Journal of Applied Phycology,* 20: 567–570.

Newkirk, G. 1996. Sustainable coastal production systems: A model for integrating aquaculture and fisheries under community management. *Ocean & Coastal Management,* 32: 69–83.

Nilsson, H.C. & Rosenberg, R. 2003. Effects on marine sedimentary habitats of experimental trawling analysed by sediment profile imagery. *Journal of Experimental Marine Biology and Ecology,* 285: 453–463.

Nowak, B.F. 2007. Parasitic diseases in marine cage culture – An example of experimental evolution of parasites? *International Journal for Parasitology,* 37: 581–588.

Pearson, T.H. & Rosenberg, R. 1978. Macrobenthic succession in relation to organic enrichmant and pollution of the marine environment. *Oceanography and Marine Biology: Annual Review,* 16: 229–311.

Pitta, P., Tsapakis, M., Apostolaki, E.T., Tsagaraki, T., Holmer, M. & Karakassis, I. 2009. Ghost nutrients' from fish farms are transferred up the food web by phytoplankton grazers. *Marine Ecology – Progress Series,* 374: 1–6.

Psarra, S., Tselepides, A. & Ignatiades, L. 2000. Primary productivity in the oligotrophic Cretan Sea (NE Mediterranean): seasonal and interannual variability. *Progress in Oceanography,* 46: 187–204.

Rapp, P., Ramirez, W.R., Rivera, J.A., Carlo, M. & Luciano, R. 2007. Measurement of organic loading under an open-ocean aquaculture cage, using sediment traps on the bottom. *Journal of Applied Ichthyology,* 23: 661–667.

Read, P. & Fernandes, T. 2003. Management of environmental impacts of marine aquaculture in Europe. *Aquaculture,* 226: 139–163.

Roberts, S. & Hirshfield, M. 2004. Deep-sea corals: out of sight, but no longer out of mind. *Frontiers in Ecology and the Environment,* 2: 123–130.

Samuelsen, O.B., Lunestad, B.T., Husevag, B., Holleland, T. & Ervik, A. 1992. Residues of oxolinic acid in wild fauna following medication in fish farms. *Diseases of Aquatic Organisms,* 12: 111–119.

Samuelsen, O.B., Torsvik, V. & Ervik, A. 1992. Long-range changes in oxytetracycline concentration and bacterial-resistance towards oxytetracycline in a fish farm sediment after medication. *Science of the Total Environment,* 114: 25–36.

Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J., Valle, C., Dempster, T., Tuya, F. & Juanes, F. 2008. Interactions between bluefish *Pomatomus saltatrix* (L.) and coastal sea-cage farms in the Mediterranean Sea. *Aquaculture,* 282: 61–67.

Sanz-Lazaro, C. & Marin, A. 2009. A manipulative field experiment to evaluate an integrative methodology for assessing sediment pollution in estuarine ecosystems. *Science of the Total Environment*, 407: 3510–3517.

Snelgrove, P.V.R. & Smith, C.R. 2002. *A riot of species in an environmental calm: The paradox of the species-rich deep-sea floor*. Taylor & Francis Ltd. London.

Soto, D., Arismendi, I., Di Prinzio, C. & Jara, F. 2007. Establishment of Chinook salmon (*Oncorhynchus tshawytscha*) in Pacific basins of southern South America and its potential ecosystem implications. *Revista Chilena de Historia Natural,* 80: 81–98.

Soto, D., Jara, F. & Moreno, C. 2001. Escaped salmon in the inner seas, southern Chile: Facing ecological and social conflicts. *Ecological Applications,* 11: 1750–1762.

Soto, D. & Norambuena, F. 2004. Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale mensurative experiment. *Journal of Applied Ichthyology,* 20(6): 493–501.

Sutherland, T.F., Petersen, S.A., Levings, C.D. & Martin, A.J. 2007. Distinguishing between natural and aquaculture-derived sediment concentrations of heavy metals in the Broughton Archipelago, British Columbia. *Marine Pollution Bulletin,* 54: 1451–1460.

Svane, I. & Barnett, J. 2008. The occurrence of benthic scavengers and their consumption at tuna farms off Port Lincoln, South Australia. *Journal of Experimental Marine Biology and Ecology,* 363: 110–117.

Tacon, A.G.J. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture,* 285: 146–158.

Tacon, A.G.J. & Metian, M. 2009a. Fishing for aquaculture: non-food use of small pelagic forage fish-a global perspective. *Reviews in Fisheries Science,* 17: 305–317.

Tacon, A.G.J. & Metian, M. 2009b. Fishing for feed or fishing for food: Increasing global competition for small pelagic forage fish. *Ambio,* 38: 294–302.

Thetmeyer, H., Pavlidis, A. & Chromey, C. 2003. *Interactions between wild and farmed fish*. The Meramed project, Newsletter 3.

Thorstad, E.B., Fleming, I.A., McGinnity, P., Soto, D., Wennevik, V. & Whoriskey, F. 2008. Incidence and impacts of escaped farmed Atlantic salmon *Salmo salar* in nature. *NINA Special Report,* 36: 110 pp.

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H. & Fang, J.G. 2009. Ecological engineering in aquaculture – Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture,* 297: 1–9.

Tuya, F., Sanchez-Jerez, P., Dempster, T., Boyra, A. & Haroun, R.J. 2006. Changes in demersal wild fish aggregations beneath a sea-cage fish farm after the cessation of farming. *Journal of Fish Biology,* 69: 682–697.

Valdemarsen, T., Kristensen, E. & Holmer, M. 2009. Metabolic threshold and sulfide-buffering in diffusion controlled marine sediments impacted by continuous organic enrichment. *Biogeochemistry,* 95: 335–353.

Vezzulli, L., Moreno, M., Marin, V., Pezzati, E., Bartoli, M. & Fabiano, M. 2008. Organic waste impact of capture-based Atlantic bluefin tuna aquaculture at an exposed site in the Mediterranean Sea. *Estuarine Coastal and Shelf Science,* 78: 369–384.

Vita, R., Marin, A., Jimenez-Brinquis, B., Cesar, A., Marin-Guirao, L. & Borredat, M. 2004a. Aquaculture of Bluefin tuna in the Mediterranean: evaluation of organic particulate wastes. *Aquaculture Research,* 35: 1384–1387.

Vita, R., Marin, A., Madrid, J.A., Jimenez-Brinquis, B., Cesar, A. & Marin-Guirao, L. 2004b. Effects of wild fishes on waste exportation from a Mediterranean fish farm. *Marine Ecology – Progress Series,* 277: 253–261.

Ward, L., Grizzle, R.E., Bub, F.L., Langan, R., Schnaittacher, G. & Dijkstra, J.A. *Site description and environmental monitoring: Report on activities from fall 1997 to winter 2000*. Internal Document, UNH OOA Environmental Monitoring. 2001.

Ward, L., Grizzle, R.E, Fredriksson, D.W. & Irish, J.D. *UNH OOA Environmental Monitoring Program*. Annual Progress Report. CINEMar OOA Internal Report. 2004.

Whitmarsh, D. & Palmieri, M.G. 2009. Social acceptability of marine aquaculture: The use of survey-based methods for eliciting public and stakeholder preferences. *Marine Policy,* 33: 452–457.

Wildish, D.J., Hargrave, B.T. & Pohle, G. 2001. Cost-effective monitoring of organic enrichment resulting from salmon mariculture. *Ices Journal of Marine Science,* 58: 469–476.