Impacts of marine farming on wild fish populations

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7. Executive Summary

As attached.

8. Objectives

1. To describe and assess the impacts of marine farming on wild fish populations.

9. Methods

The literature review was conducted by searching Aquatic Sciences and Fisheries Abstracts on the search terms +aquaculture +impact, writing to authors of recent articles located in the search requesting relevant articles, and using the reference lists of the articles obtained as "seed" references. The initial search revealed about 1600 references, of which about 300 are cited here.

10. Publications

Endnote database of publications viewed attached.

Impacts of marine farming on wild fish populations

1. Overview and approach

I have reviewed the international literature regarding the impacts of marine farming as it applies to the New Zealand situation. "Marine farming" in this context refers to the deployment of organisms in situations that are controlled by humans. Estuarine and intertidal areas are included. Other reviews have been offered (e.g., Iwama 1991, Wu 1995, Beardmore et al. 1997, Kaiser et al. 1998, Black 2001) for different geographic areas and with varying focuses, but the conclusions do not necessarily apply to New Zealand sites, species, and techniques. Holland & Jeffs (2000) provide a brief overview of aquaculture in New Zealand. Sinner (2000) included consideration of environmental effects of marine farming in his review of the environmental effects of the seafood industry, but the primary focus was management-oriented, and additional information is available now. I have speculated on future developments in marine farming techniques and sites in the discussion. Generally studies of species absent from New Zealand have been ignored, except in the context of process-oriented research. Where studies pertaining to the New Zealand situation are available they are considered in detail. Overseas studies are mainly used to support and expand on important processes.

The review has been divided into sections: impacts on the water column (2); impacts on the benthic environment (3); litter impacts (4); introduction of pests with structures (5); buildup of predators under and around farms (6); displacement of fishing (7); genetic impacts (8); disease risk (9); transmission of parasites (10); influences of aquaculture of wild species on their local abundance (11); effects of toxic algal blooms (12); future aquaculture in New Zealand (13); and a summary and conclusion.

1.1 Aquaculture in New Zealand

Exact earnings from aquaculture in New Zealand are difficult to discern, but information from SeaFIC website (http://www.seafood.co.nz) indicates that in 2000 roughly 20% of the NZ$1.56 billion earnings from fisheries (i.e. $320 million) was derived from aquaculture in 2000. The major earner is greenshell™ mussels, but a variety of other species, including salmon and oysters, also contribute. Considerable growth in aquaculture is predicted.

2. Impacts on the water column

2.1 Background

Aquaculture may change the physical, chemical, and biological properties of the water column. Aquaculture structures may modify the physical properties of the water column by reducing wave action and altering the flow rate. Optical properties of the water column may be changed by addition or removal of materials, or by shading due to structures. Another physical property of water that is changed by aquaculture is flow rate. Chemical properties may be changed by the organisms or structures on the farms removing or adding material to the water column, for example the addition of excreted nitrogenous waste by farmed organisms to the water column. Biological properties of the water column may be changed by the cultured species selectively removing particular organisms from the water column, as for the removal of phytoplankton by mussel farms.

Elsewhere in the world the water in aquaculture systems may be deliberately heated to alter its properties. In tropical pond systems chemical fertilisers are widely applied to induce blooms of algae as food. Similarly water treatment compounds, such as pH adjusting chemicals, oxidising agents, flocculants, coagulants, osmoregulators are often applied (Joint FAO/NACA/WHO Study Group on Food Safety Issues Associated with Products from Aquaculture 1997). Algicides, herbicides, and piscicides are also used, primarily in temperate freshwater ponds and tropical ponds, and these techniques or applications are not used in New Zealand. Disinfectants such as benzalkonium chloride, polyvidone iodine, glutaraldehyde, formalin and hypochlorite may be used during the processing stages, but they are not used in aquaculture in New Zealand either.

2.2 Shellfish farming impacts

The physical effects of shellfish farms obviously vary with the structures on which they are deployed. In New Zealand, mussels are generally farmed on longlines, whereas oysters are usually grown on intertidal rack systems. There have been some experimental attempts to grow oysters on longlines, but failure to attain market quality has hindered scaled-up production (S. Handley, pers. obs.). The physical effects of proposals to culture other species (such as sponges) may be assessed on the basis of their physical dimensions.

2.2.1. Mussels

New Zealand

Hickman (1980) provided a review of the environmental conditions necessary for the culture of mussels, Hickman (1983) contributed a bibliography of New Zealand mussels in general, and Jeffs et al. (1999) published a more recent bibliography of the greenshell™ mussel.

Most cultured bivalves are lamellibranchs, which feed by filtering particles out of the water through the gills. Mucus on the surface of the gills is used to bind particles into strings. Some sorting occurs, with rejected particles being ejected in the exhalant respiratory stream (as pseudofaeces), whereas particles suitable for consumption are coated in mucus, wound into the gut, and ingested. Faeces and pseudofaeces may fall to the seabed, and the descent of those pellets to the seabed may be viewed as an impact on the water column.

The oceanography of marine farming areas has important effects on the pelagic impacts of mussel farms. Where currents are slow, the mussels are in contact with a body of water for longer, and thus are able to filter out more material from the water column, and therefore there is more scope for depletion. Rapid currents provide less opportunity for water column phytoplankton depletion within the farm boundaries. Pelagic impacts are also linked to the economic viability of the farm site, as sites where farms strip out much of the phytoplankton will have poor growth. The mussel lines may themselves modify current rates passively, so that currents are slowed within the farm. At present current flows within and around farms are not well-understood, though NIWA research is addressing this issue.

Water clarity may be increased in and immediately downstream of mussel farms, due to the removal of particulate matter, including phytoplankton (Grange & Cole 1997). Divers commonly observe this when swimming down through mussel farms; the water is relatively clear in the upper areas among the lines, whereas there is much more material in the water column below the farm lines (R. Cole, pers. obs.). Removal of phytoplankton is the best known and best studied biological impact of shellfish aquaculture on the water column. Waite (1989) suggested that food might be reduced by up to 60% within farm boundaries. He suggested that those effects occurred within farms, and that no effects were detected between farms (i.e. beyond farm boundaries). Grange & Cole (1997) summarised the findings of phytoplankton surveys inside and outside farms, and suggested that in most cases the phytoplankton depletion zone was limited to within 80 m of the farm. However, more recent surveys suggest that these patterns may not be general, and in some situations the depletion halo may extend further (A. Ross, pers. comm.). The most detailed study described feeding responses by greenshell™ mussels *Perna canaliculus*, to variations in quality and quantity of seston (Hawkins et al. 1999). Low phytoplankton concentrations (1–2 $\mu g\ l^{-1}$) allowed maximal phytoplankton clearance rates, and only at seston concentrations above 1 $g\ l^{-1}$ total dry particulate mass did overloading of filtering ability occur. James et al. (2001) suggest that at low food levels *Perna canaliculus* is non-selective. However, the picture of phytoplankton depletion by farms is complicated as nutrient (nitrate and ammonium) regeneration from mussels within farms may also contribute to phytoplankton growth (Ogilvie et al. 2000). Gibbs et al. (1992) identified deepwater chlorophyll *a* beneath mussel farms, and suggested that internal waves moved that phytoplankton vertically by up to 6 m and into marine farms on occasions.

Links among flow, nutrients, and phytoplankton are also important at a larger scale. For New Zealand they have been considered in most detail for Pelorus Sound, where influx of freshwater from the Pelorus River appears to be important in stabilising the water column, leading to high productivity (summarised in Ross et al. 1998, MacKenzie 1998). A series of comprehensive physical investigations formed the basis of the study of Ross et al. (1998) (Bradford et al. 1987, Vincent et al. 1989, Gibbs 1993, Gibbs et al. 1991, 1992, Gibbs & Vant 1997, Sutton & Hadfield 1997, Proctor & Hadfield 1998). Brock et al. (1985) noted a link between freshwater input and faecal coliforms. That link is important to maintain microbiological health standards, and the Nelson/Marlborough Shellfish Sanitation Programme uses catchment specific predictive relationships between rainfall and faecal coliforms to determine when it is safe to harvest shellfish for export markets. Rather less research has investigated the local effects of marine farms on water flows, though Morrisey & Swales (unpubl. report) suggest that current speeds within farms may be 30% of those outside farms.

Ogilvie et al. (2000) investigated spatial and temporal variability in phytoplankton abundance. They noted that Murdoch & Oliver (1995) did not find lower abundances of phytoplankton within farm boundaries, whereas Grange & Cole (1997) did. Ogilvie et al. suggested that phytoplankton reduction might be localised (even within farms), noting that greater reserves of phytoplankton occurred at depth (7–17 m) but also acknowledged that it might be qualitatively different from that higher in the water column. There is concern in the marine farming industry regarding stripping of phytoplankton from the water column, as farming intensity increases. Modelling approaches are being used to investigate the sustainability of farming in different parts of the Marlborough Sounds (NIWA, unpubl.), but as yet these results are site-specific.

Mussels may ingest phytoplankton on mussel farms, as may the abundant epifaunal invertebrates that also occur on mussel lines (e.g., ascidians, bryozoans). In the water column, as well as phytoplankton, there may be bacteria, protozoa, detritus and inorganic matter, of which detritus and bacteria are thought to be less important as food for mussels. Davenport et al. (2000) found that *Mytilus edulis* killed zooplankton by inhaling them. Items < 3–6 mm long were ingested, whereas non-ingested (> 3–6 mm) individuals died and were expelled as pseudofaeces. It is unknown whether *Perna canaliculus* has a similar impact but the lower density of zooplankton than phytoplankton (tens of zooplankton individuals per litre typically, as opposed to thousands of phytoplankton cells per ml) means that the effects are likely to be small. There is potential for a direct impact of mussels on eggs of fish species. (Larvae are less likely to be affected because they are mobile). However, marine reserve studies (e.g., Davidson 2001) suggest that the major influence on blue cod in Queen Charlotte Sound, where there is very limited mussel farming, is recreational angling. Detailed information regarding the abundance of fishery species in Pelorus Sound is lacking at present, but if small fish were abundant in areas with many marine farms, it would suggest that the fish populations are not limited by recruitment, and that the impacts of marine farming on planktonic larvae were small. Impacts of mussels on zooplankton remain to be documented in New Zealand or for New Zealand species; studies are imminent however (J. Zeldis, pers. comm.).

Changes in nutrient cycling

Likely effects of aquaculture on nutrient cycling include excretion of nutrients in more bioavailable forms, release of nutrients from biodeposits below farms, and loss of nutrients due to harvesting. Generally, because water movement is high in most areas of coastal aquaculture, nutrient recycling has been little affected by marine farming. However, nutrient concentrations have been altered by aquaculture in some situations (e.g., Marlborough Sounds – Gibbs et al. 1992; Big Glory Bay – Pridmore & Rutherford 1992). Kaspar et al. (1985) measured elevated concentrations of ammonium and sulphides below a mussel farm in Kenepuru Sound.

Members of the Ministry of Fisheries Aquatic Environment Working Group (AEWG) raised questions regarding the impact of mussel farms on dissolved oxygen levels over a diurnal cycle. The main dissolved oxygen sources are exchange across the water surface with atmospheric oxygen, and photosynthetic production by marine plants. Decomposition processes at the sediment surface are the primary sink (place where losses occur). Phytoplankton switch from photosynthetic oxygen production during daylight to oxygen consumption via respiration at night. Marine plants (such as benthic diatoms and perhaps macroscopic plants) may occur at the sediment surface in marine farming areas (e.g., Tasman Bay and Marlborough Sounds – Gibbs 2001, Big Glory Bay – Gillespie 1989), but whether these contribute to oxygen production depends on water depth; most marine farms occur in >20 m of water, and photosynthetically active radiation is low at the seabed. The major effects in the water column at night will reflect the small changes from aquatic plants switching from photosynthesis to respiration. Gibbs et al. (1992) sampled three inner Pelorus Sound sites over 24 hrs, and found little evidence of daily-cycle effects on dissolved reactive phosphorus, chlorophyll *a*, or particulate phosphorus. Gibbs (2001) shows data from Tasman Bay which indicates that temperature, chlorophyll *a* and turbidity change little over a 24-hr period. Day-night differences are therefore unlikely to obscure or confound the results of daytime surveys of water column variables.

Davidson (1998) documented water column impacts of mussel harvesting. Harvesting occurs throughout the year with specialised equipment on harvesting barges. The longline backbone is secured with hooks as the boat draws alongside, and the continuous dropper line is fed into a stripper that removes mussels. Mussels are cleaned with high pressure water. Both the raising and stripping stages disturb sediment from the droppers, but the greatest source of sediments when harvesting comes from the deck discharges of the harvester. The discharge contains fine sediments that have settled from the water column onto the mussels, pseudofaeces from the mussels, and animals and plants. The latter were characterised as comprising mussels (both Greenshell™ and *Mytilus edulis galloprovincialis*), ascidians, bryozoans (*Watersipora cucullata*, *Bugula* sp.), crustaceans, and seaweeds (including *Codium fragile*, *Colpomenia sinuosa*, *Cystophora* spp.). Davidson also noted that in some areas the introduced Japanese seaweed *Undaria* occurred on the upper areas of the lines. Visible effects of harvesting had vanished within 25–30 m distance of harvesting, and within 90 mins from the time of harvesting. Gibbs et al. (1992) suggested that some patterns in water clarity in their study were related to the effects of harvesting, and that the effects of the plume (increased turbidity) extended to a depth of about 4 m.

Davidson (1998) suggested that the harvesting discharge would vary with location, wave exposure, tidal currents, depth of droppers, position within a farm, mussel stage at harvest, seeding rates, timing of seeding and line deployment, and mussel over-growth, including over-settlement of blue mussels. He suggested that a detailed study of mussel harvesting impacts should include consideration of geographic locations, wave exposure, tides, stage of mussels at harvest, and compare harvesting vs farm operating impacts. Davidson (1998) concluded that discharge from mussel harvesting had an obvious visual impact that might extend beyond the farm boundaries, and a more localised effect on the seafloor.

At present links between consumption of phytoplankton production by intensive aquaculture and wild fish populations in New Zealand are tenuous. While phytoplankton may be depleted near marine farms, there is little evidence – from either local or overseas studies – to indicate that other populations of organisms in the water column might be impacted by that depletion. Process-oriented studies and finer scale sampling to clarify the spatial extent of interactions between mariculture and the environment would assist.

2.2.2 Overseas

Studies in France (Raillard & Menesguen 1994) have documented declining aquacultural productivity owing to overstocking. At the embayment level, modelling approaches are often used to predict carrying capacities (Grant et al. 1993), and numerical models are routinely used in assessing the suitability of sites for marine farms. In Ria de Arosa Spain, mussel-rafts provide substrata for abundant standing crops of brown and green algae. The algae are estimated to provide 8% of the total productivity of the area, though rafts only occupy 1% on an areal basis. Navarro et al. (1991) found that upstream rafts (ones that receive water first) in Ria de Arosa have the greatest scope for growth, which is consistent with an impact on the water column.

Pitcher & Calder (1998) studied the productivity of mussel culture in Saldanha Bay, South Africa. They indicated the importance of upwelling to nutrient supply and thus phytoplankton productivity, but noted that wind-driven circulation within the bay dominated over tides. A finer scale study at the same area (which contains most of the mussel aquaculture in South Africa) found effects of raft culture on water flows (Boyd & Heasman 1998), and provided estimates of flow of 7.5 cm s^{-1} within farms, and 1.5 cm s^{-1} within rafts (i.e. an 80% reduction in flow rate). Heasman et al. (1998) showed that spacing the ropes more widely on rafts increased harvest by 30%.

The types and configurations of growing structures, mussel species, and oceanography of the sites in the overseas studies are sufficiently different from those in New Zealand that I view them as being of limited applicability, other than for providing general background. Furthermore, the fish populations in those areas are quite different from those in New Zealand, and there are good reasons to doubt that the effects of mussel farming as described overseas would apply in New Zealand.

2.2.3 Oysters

The main oyster cultured in New Zealand is the Pacific oyster *Crassostrea gigas*. It was introduced to New Zealand sometime in the late 1960s (Dinamani 1971). Increasing intensity of farming may have caused growth rates to decline, and mortality rates to increase (Ren et al. 2000). Oysters grown on deepwater longlines (Handley 1995) are likely to have similar impacts to mussels (see 2.2.1 above). However, effects on water clarity are unlikely to be detected, as oysters are generally grown in turbid estuarine waters. Water column clarity might decrease round oyster rack farms if increased sedimentation occurred within the farm boundaries (e.g., Forrest 1991), and that sediment was then resuspended by wave activity.

Feeding, energetics and physiology of oysters has been considered in some detail (Ren et al. 2000), as a basis for improving the management of aquaculture. Morphometrics, clearance rates, filtration rates, ingestion rates, absorption efficiencies and oxygen consumption rate were quantified, but that study contained little discussion of environmental effects. The results indicate tolerance of the oysters to high levels of sediment in their diet.

A NIWA study detected phytoplankton blooms in Mahurangi Harbour after significant land-based discharges (S. Handley, unpubl.). Oyster farms could potentially mitigate eutrophication in areas with significant terrestrial run-off, by feeding on plankton and thus absorbing nutrients from the land. It is not known whether sustainability in oyster-growing harbours is controlled by nutrients derived from offshore (driven by climatic events) or terrestrial nutrient inputs (S. Handley, pers. comm.). Disturbance by wave action damages shells and may reduce growth rates (Quayle 1988, Visser

1993). Visser (1993) carried out an experiment examining growth of oysters with respect to wave exposure, but found no effects.

A large number of studies have investigated near-bed shellfish feeding (Table 1 − includes some investigations of benthic mussel beds). Dense beds of shellfish can deplete water of food as it passes over them. The best-known incidence of this is in the intertidal, where water is serially depleted as it passes over dense beds of shellfish, typically on incoming tides (e.g., Peterson & Black 1991). Although most studies of that interaction have not been done in an aquaculture context, there is the potential for it to be important (e.g., Boyd & Heasman 1998). Investigations in Tory Channel and Tasman Bay (Gillespie et al. 2000) indicate that microalgal communities on the seabed can contribute to the benthic food web. Those studies generally indicate that the benthic microalgal communities can contribute greatly to the nutrition of shellfish. No such studies have clearl shown this in New Zealand, but cockles, dredge oysters, Pacific oysters etc. are all potentially influenced by that process.

Table 1. Studies investigating near-bed seston effects of bivalve species.

Study	**Location**	**Organism**
Bock & Miller 1994	Delaware, USA	*Mercenaria mercenaria*
Frechette et al. 1989	St Lawrence River, Canada	*Mytilus edulis*
Frechette & Grant 1991	St Lawrence River, Canada	*Mytilus edulis*
Grant et al. 1990	Nova Scotia	*Ostrea edulis*
Muschenheim & Newell 1992	Maine	*Mytilus edulis*
Prins & Smaal 1994	Oosterschelde, Netherlands	*Mytilus edulis*
Prins et al. 1991	Oosterschelde, Netherlands	*Mytilus edulis*, *Cerastoderma edule*
Smaal & Haas 1997	Oosterschelde, Netherlands	*Mytilus edulis*, *Cerastoderma edule*
Ten Brinke et al. 1995	Oosterschelde, Netherlands	*Mytilus edulis*
Widdows et al. 1979	SW England	*Mytilus edulis*
Wildish & Kristmanson 1984	St. Andrews, Canada	*Mytilus edulis*, *Modiolus modiolus*

Mazouni et al. (2001) investigated the biofouling communities on rope culture of *Crassostrea gigas*. They cited studies indicating 2.7−14 kg of biofouling per line (lengths probably 3−4 m). Ascidians dominated the fouling species, which also included bryozoans, sponges, polychaetes, and macroalgae. Lesser et al. (1992) concluded that competition between blue mussels and the biofouling community (dominated by an ascidian and a suspension-feeding gastropod) was unlikely to have negative effects on the mussels. A recent bloom of the ascidian *Ciona intestinalis* in the Marlborough Sounds had the potential for important negative effects, but did not become a production issue.

Dewey (2000) summarised opposing points of view regarding the pelagic effects of shellfish growing. That study cites the ability of shellfish to remove large volumes of phytoplankton (which in the US can cause dissolved oxygen starvation and block light from seagrasses and seaweeds) as a positive environmental effect. Dewey (2000) also cites citizens' groups filing suits against the aquaculture industry for discharges of pseudofaeces and faeces. No such situation exists under New Zealand legislation at present.

In shallow areas, such as those occupied by intertidal oyster racks, resuspension of detrital organic matter may be important. That organic matter may decrease phytoplankton production by masking light, so that complex interactions arise. Ren et al. (2000) investigated oyster feeding and confirmed that oysters are able to consume both phytoplankton and sediments. Morrisey & Swales (unpubl. report) suggest that in the Mahurangi Harbour increasing densities of farm racks may have caused declining farm yields.

There is little information regarding the fauna that may live on and among crop bivalves, although it may have important effects. The fauna typically comprises hydroids, ascidians, sponges, and other invertebrates. As all these groups are filter-feeders, and the sponges at least may have high filtration rates, there is potential for interactions between bivalves and the associated species, for example, in competition for phytoplankton food, crowding, aggressive interactions (such as stinging), and crushing. None of these interactions are well-understood, yet they comprise the day-to-day environment of harvested bivalves. Seaweeds growing epiphytically on shells may also have physical impacts, by reducing current flows, increasing drag on shells etc. Small mobile invertebrates also live among the crop, and triplefin fish occur; their abundance and importance awaits investigation.

2.2.4 Water column – Other shellfish

I could locate no New Zealand studies that have investigated the depletion of suspended material from the water column over tidal flats or subtidal sediments. However, given the density of some bivalves (e.g., pipi *Paphies australis* in northern estuaries – Cole et al. 2000a, cockles on intertidal sandflats – McArdle & Blackwell 1989) and their filtration efficiencies, it is obvious that material from the water column (phytoplankton, seston, resuspended sediments, etc.) will be filtered out, and redeposited in more concentrated form. The fate of such material is unknown, but it may be refiltered several times in areas where wave action is sufficient to resuspend it (i.e., intertidal areas, and wave-exposed subtidal areas).

2.2.5 Summary

Mussel farming has effects on water flows, phytoplankton concentration, water clarity, and nutrient composition. The relative importance of this to natural systems will depend on the conditions at a site, and may also vary seasonally. The impacts will depend on the local situation, and on factors such as the density of organisms in the surrounding environment, their sensitivity to phytoplankton depletion and its variability, their scope to respond to elevated nutrients etc. Phytoplankton is removed by mussel farms, and coastal nutrient enrichment may be lessened by intensive bivalve culture. Depletion shadows around mussel farms are poorly understood, as are cumulative effects of several farms, within an embayment or at larger scales. Effects on zooplankton organisms are possible, but undocumented. Studies in areas without marine farming implicate other possible mechanisms for reduced sizes of benthic fishes with plantktonic larval phases. It is possible that there are effects of farming other species, but these have not been investigated in the detail that mussels have been.

2.3 Finfish farming impacts

Finfish culture differs from that of shellfish farming in that food must be added, whereas shellfish use natural phytoplankton for food. Most of those impacts derive from waste feed, even though technological advances have increased conversion efficiencies. Finfish farms may directly alter current flows. Criteria for siting farms have frequently been based on flow rates, since adequate water circulation is fundamental for finfish culture. Physical effects of farms are not well-described, but there are reports of incidences of decreased water flow due to dense jellyfish (probably *Aurelia aurita*) populations (M. Sowden, Big Glory Seafoods, pers. comm.).

Pearson & Black (2001) usefully summarised the pelagic impacts of marine fish cage culture, and the following summary follows their treatment. Cage culture in New Zealand at present is mainly of salmon in similar environments to those in which salmon farming is done overseas. Therefore the overseas considerations and predictions of modelling are much the same as for the New Zealand situation. Waste products that leave the farm include ammonia, phosphorus, dissolved organic carbon, dissolved organic nitrogen, and dissolved organic phosphorus. Lipids are often visible on the surface after feeding. In marine waters, nitrogen is usually assumed to be the nutrient that limits phytoplankton growth (although there may be exceptions). The effects of dissolved wastes depends on their concentration, which are functions of the speed at which they are diluted. One critical parameter is flushing time, which determines whether nutrients will build up within an area. For semi-enclosed embayments, a simple method of estimating flushing time is available (Strutton et al. 1996). That approximation allows rough estimations to be carried out. An alternative method is to use planar area and volumes of water in the formula of Edwards & Sharples (1986).

Though widely discussed in the popular literature, there is no clear evidence of links between aquaculture and algal blooms (Wu 1995). In the northern Baltic, nutrients from rainbow trout farms are thought to have led to production of algal mats, that have impacted on the fauna of the area. Sorokin et al. (1996) suggested that a toxic phytoplankton bloom in an Italian lagoon was linked to aquaculture. Pearson & Black (2001) suggest that aquaculture is not implicated in the global rise of reported harmful algal blooms.

Nitrogen is excreted by fishes as ammonia and urea. The available data suggest that excretion of ammonia is the greatest sink for nitrogen, with feed wastage being the second greatest sink. Formulation of artificial feeds is directed at pellets remaining within the cages for as long as possible, and greatly improved efficiencies of feeding have been attained (e.g., Ang & Petrell 1998; Petrell & Ang 2001). Pearson & Black (2001) emphasise that the feeding of trash fish to carnivorous crop fish—which is widespread in the tropics—is wasteful. Wu (1995) reviewed a number of studies that found decreased dissolved oxygen and increased biological oxygen demand (BOD), and nutrients (P, organic and inorganic N, total C) in the water column near farms.

Roper et al. (1989) predicted concentrations of hydrogen sulphide under salmon cages on Stewart Island, and concluded that effects on the water column could emerge (though they did not actually detect any changes at the time). Kaspar et al. (1988) described much higher levels of ammonium, organic N and phosphorus beneath a salmon farm than in adjacent sediments, and suggested that the area affected extended about 30 m from the farm boundary. Nutrient addition from benthic deposits is thought to contribute to effects on the water column. The best-documented impacts of finfish farming within New Zealand were gathered during a phytoplankton bloom at Stewart Island. Chang et al. (1990) identified the phytoplankton species responsible for the mortality of 600 t of salmon in January 1989; MacKenzie (1991) provided background information regarding the phytoplankters and the nature of the toxicity from the bloom, whereas Pridmore & Rutherford (1992) estimated that salmon farming increased the nitrogen concentration of the bay by about 30%. There is debate and speculation regarding the contribution of nutrients from fish farming to the frequency of harmful algal blooms.

Several studies have suggested possible roles for polyculture in ameliorating the impacts of fish culture. Jones & Iwama (1991) found oysters grew significantly larger downstream of a salmon farm. Stirling & Okumus (1995) investigated culture of mussels as a method of reducing particulate organic wastes from salmon farms, and found that it produced a small improvement in mussel growth. They also identified two further issues that required addressing before integration of shellfish and finfish aquaculture might proceed; the possible concentration of therapeutants in the shellfish, and the possibility of the bivalves acting as reservoirs of pathogenic bacteria to infect the fish. Mazzola & Sara (2001) also suggested that bivalve culture near fish cages could reduce the environmental impact (by removing nutrients) and increase the profitability (from sale of bivalve crop) of finfish farming. To my knowledge, no such applications have occurred in New Zealand.

In determining the importance of the effects of aquaculture it is important to identify the context. Different characteristics of the water column will be important for different species in different areas. For example, seagrass is thought to be sensitive to water clarity, and reductions in seagrass canopy have been linked to increased turbidity. Thus, small increases in turbidity may be important where seagrasses are present, but trivial where they are absent. Elevated nutrients might increase growth rates of ephemeral algae that grow on the surface of seagrasses, and lead to shading and eventually loss. Difficult arguments will follow regarding the relative merits of preserving different species in different areas affected by the same impact. Aquaculture may increase nutrients (enhancing the growth of desirable species) but site-specific characteristics may mean that bycatch (in the fisheries sense) is also positively affected, and the negative aspects of that may outweigh the growth increase.

Modelling studies are frequently used in planning the siting of marine farms. A programme in Sweden has aimed to develop criteria, methods and models for the planning and siting of aquaculture in coastal waters in Sweden. Wallin & Haakanson (1992) describe the mechanics of that process, which at least partly rests on calculated nutrient loadings from marine fish farms in greater detail. Such models are not widely used in New Zealand at present because of the small number of salmon farms, but could be used should finfish farming expand.

Summary

Marine fish farming can have important physical, chemical and biological effects on the pelagic environment. Although modelling of water flows is an important tool overseas, such models are only beginning to be used in New Zealand. There is considerable scope for additional research regarding pelagic effects of aquaculture activities.

3. Impacts on the benthic environment

Effects on physical (e.g., grain size composition), chemical (e.g., addition of heavy metals), and biological characteristics (e.g., alterations to fauna) of the seabed are considered here. Benthic species near marine farms may be subject to food depletion, nutrient addition or depletion, modified flows, enrichment via food items and faecal material, and smothering by shells.

3.1 Shellfish

Shelldrop is prominent under New Zealand oyster farms (Forrest 1991, 1994) and mussel farms (Forrest 1994, Cole & Grange 1996), despite the very different natures of the environments in which the two species are grown. There have been two parallel foci of research in this area; one on benthic micro-organisms (by Cawthron Institute) and another on the macrofauna (by NIWA).

3.1.1 Mussels

New Zealand

Oliver (unpubl.) described average rates of sedimentation (dry weight) of nearly 30 g m^{-2} day^{-1} below mussel long-lines in Beatrix Bay, Kaspar et al. (1985) described the buildup of mussel shells beneath mussel farms in Kenepuru Sound, Marlborough Sounds. Associated with those mussel shells were ascidians, sponges, calcareous polychaetes, and bivalves. No quantitative assessment of the abundances of those animals was provided however, Kaspar et al. (1988) described effects of mussel farms on sediment chemistry and microbial activity at Kenepuru Sound. It is difficult to compare this study with others, as few other studies have examined microbial activity. The seabed at Kenepuru Sound has much finer grain size, and is shallower than many areas in which marine farming is done.

Gillespie (1989) described benthic impacts of mussel farming in a report to the Department of Conservation. That report focused on Big Glory Bay, Stewart Island, and included information regarding current flows. Gillespie (1989) emphasised the role of current flows in determining the footprint of the farm. He described “meadows” of the red alga *Lenormandia*, and suggested that existing holes in the canopy might result from salmon farming impacts. Gillespie suggested that most of the mussel drop-off occurred at the time of harvesting, and that organic enrichment would be more severe where currents are small. He identified impacts on particular habitat types (seaweed beds, shellfish beds, reef), and considered the impact on *Lenormandia* beds to be severe. Predators associated with mussels on the seabed such as *Coscinasterias* were suggested to have possible effects on surrounding infaunal species.

De Jong (1994) studied a mussel farm in Manaia Harbour, Coromandel, and suggested that benthic impacts were usually limited to within 10–20 m of the lines. Impacts included finer sediments with more organic matter, and lower dissolved oxygen and pH values under the farm than nearby. De Jong considered that physical and chemical variables demonstrated impacts more clearly than biological variables. Sediments within his study farm had smaller grain sizes, and higher percentages of water and organic matter than outside. Sedimentation rates were 15% higher in the farm than at nearby controls during winter, and 34% higher in summer. There were also biological impacts. He found clear alterations to the fauna, but not as might have been predicted from other studies of organic enrichment. De Jong found fewer polychaetes, a greater abundance and biomass of crustaceans, and an increase in the proportions of carnivore and suspension feeders. The organic levels in the sediments were lower than those recorded elsewhere, and mussel drop-off changed the seabed from mud to a combination of mud and mussel reef. De Jong suggested that the accumulation of mussels beneath the farms could accelerate sediment deposition, and that the extent of the impact was 10–20 m beyond the farm boundary. No clear impacts on species richness were observed, biomass was greatest toward the farm centre, overall abundance levels were greatest at the farm edge and polychaetes were less abundant toward the centre of the farm. The species that increased most notably below the farm were three crabs *Halicarcinus innominatus*, *Petrolisthes novaezelandiae* and *Notomithrax minor*, the sea star *Coscinasterias calamaria (*now *muricata*), whereas the polychaetes *Lumbrinereis* and *Aglaophamus* were suggested as being suitable indicator organisms for impacts.

De Jong (1994) also suggested other benthic effects, such as increased abundance of *Coscinasterias* and spotties, and grazing by parore *Girella tricuspidata* (a northern New Zealand species). Recovery from farming after removal was predicted to be slow (though there were no data). De Jong estimated that mussel faecal pellets settled at a rate of 0.0118 m s^{-1} and that clumps of mussels on the seabed reached densities of up to 250 m^{-2}, with a cover of about 38%. I can find no mention of a depth at the site (elsewhere I have found it referenced as 9 m), but the observation that the bottoms of the droppers touched the seabed at low tide (De Jong 1994: p.29) suggests that water depth was of the order of 10–12 m at the inner edge. The lack of reported depths greatly diminishes the utility of the study, and if the depth is only 9 m, restricts extrapolation of those results to other areas of greater depth.

Forrest (1994) provided photographic evidence showing that in some areas sediments below mussel farms could be greatly modified by organic enrichment. The extent of such impacts was thought to be within a few 10s of m of the edge of the farm. He also noted positive effects such as acting as a food source for other species, and forming a habitat for other species on the seabed, which may result in a localised increase in diversity. Forrest also suggested that positive effects to humans occurred as the farms aggregated fish, but noted that it was probably a localised gathering, rather than the provision of new individuals.

Anon (1995) mentioned both positive and negative impacts of New Zealand mussel farms, but emphasised visual impacts.

Cole & Grange (1996) provided a description of the abundance of mussels from the farm boundary into the farm (distances up to 100 m) on Marlborough Sounds Greenshell™ mussel farms, noting the presence of scallops *Pecten novaezelandiae*, horse mussels *Atrina zelandica*, 11-armed starfish *Coscinasterias muricata* and kina *Evechinus chloroticus* within farm boundaries. Mussel abundances were up to 350 per 5-m^2 on average, with local abundances estimated at up to 2000 per 5-m^2. They noted that in most areas droppers did not approach the seabed, so the farmed stock were separated from mussels on the seabed, and there was little chance of competition for food. Further observations suggest that there is wide variation in the extent of shelldrop among areas. Where there is long wave fetch and bowing of the mussel lines may be large, a continuous cover of shelldrop may occur, whereas in other areas very narrow, discrete rows of shell are found on the seabed. It is possible that the matrix of shells on the seabed increases localised sedimentation, by reducing currents amongst the complex shells. Such environments might therefore be areas in which mud could deposit, which would limit the usefulness of the habitat for some species. I note that there are no published observations of the abundances of organisms among shelldrop, but such areas are readily sampled. Inglis et al. (unpubl.) have characterised high abundances of starfish *Coscinasterias muricata* beneath mussel farms. The individual starfish under mussel farms are thought to be fed to satiation and were found to move little.

The severity of the impact of mussel farms on the seabed appears to vary with farm age (intensity) and exposure to wave action (area affected), but there are few quantitative data regarding the nature of the impact. Insufficient data from quantitative benthic samples, taken near marine farms, are in the public domain to form conclusions.

Much of the concern regarding marine farming has stemmed from its perceived effects on fishery species in the Marlborough Sounds, in particular, blue cod. As that is the area where the most intensive marine farming has occurred, the following discussion pertains mainly to that area and species. Recent (May 2001) press releases have suggested that declines in fishery species are related to, and because of, the number of mussel farms. Information regarding overall fish stocks in the Marlborough Sounds comprise potting surveys of blue cod (Blackwell 1997, 1998), comparisons of sampling via potting and diving for blue cod (Cole et al. 2001), marine reserve studies (Cole et al. 2000b, Davidson 2001), and scuba counts in the outer Marlborough Sounds/greater Cook Strait area (NIWA unpub.). Carbines (1999) assessed likelihood of mortality in relation to handling during recreational angling. The assessments of blue cod stocks that have been carried out to date have primarily used potting (Blackwell 1997, 1998), which Cole et al. (2001) showed is biased toward larger fish. Whereas it is adequate as a fishery assessment technique, potting cannot be used to assess recruitment (in the non-fishery sense of recruitment to benthic populations, rather than recruitment to the fishery).

Articles in the popular press, and submissions at marine farm resource consent hearings suggest that some sectors of the community have concerns regarding the status of fish populations in the Marlborough Sounds. The data that are available indicate declines in numbers and sizes of blue cod in the Marlborough Sounds over the last 8–9 years (Davidson 2001). No New Zealand studies that I reviewed conclusively show that marine farming is responsible for, or correlated with, abundance of fishery species. Such data would comprise assessments of numbers of fish in areas with and without mussel farms, preferably both at the farm and embayment scale. As there are numerous areas without marine farms interspersed with areas that have marine farms in the Marlborough Sounds (see Marlborough District Council 1999) there is no reason that such a comparison could not be carried out. Davidson (2001) provided a long time-series of data for blue cod in outer Queen Charlotte Sound, in areas where there is no marine farming or commercial fishing. Those data show that in the absence of recreational fishing blue cod abundances was double that outside the reserve. Moreover, patterns through time in the size structure of the population (as sampled by line fishing) mirrored changes in minimum legal angling size. Data from diving surveys (Cole et al. unpubl.) indicate that blue cod are abundant in outer Queen Charlotte Sound, but that most of the fish are small. Otherwise, no data have been supplied to support arguments that marine farming is a factor in the decline of fish stocks. I conclude that there is strong evidence that—in Queen Charlotte Sound at least—blue cod population size structure is controlled by recreational fishing, rather than aquaculture. There are no comparable data from Pelorus Sound, but on the basis of surveys of recreational angling (e.g., Bell & Associates 2000) it appears reasonable to expect that a similar situation would occur there.

International

International literature has considered the benthic impacts of mussel farming (e.g., Ten Brinke & Donkers 1993, Kautsky & Evans 1987). Generally sedimentation below mussel farms appears to be increased by a factor of 2 or 3 compared to areas outside the farms. Farm sediments tend to be finer-grained, and are rich in organic matter and sulphides. Sediments below farms represent a substantial nitrogen pool. Increased sedimentation rates derive from faecal pellets which increase the organic content of the seabed sediments. Elevated organic content can lead to sediments being more reduced, the pore water becomes more acidic, and release of chemical byproducts can lead to a stripping of dissolved O_2 from the sediments and bottom waters. In extreme cases anaerobic bacteria can convert the nutrients, releasing toxic hydrogen sulphide. Such sediments are usually black. Ultimately such processes can lead to anoxic areas, both vertically within the sediments, and also in the water column. The species composition of infauna reflects how deep oxygen penetrates into the sediments.

The most focussed studies of effects of mussel farming on the fauna of surrounding areas come from Galicia, Spain, where *Mytilus galloprovincialis* is cultured intensively (Freire 1996, Fernandez et al. 1995, Freire & Gonzalez-Gurriaran 1995, Freire & Gonzalez-Gurriaran 1990). That area has an ecology that is dominated by one crab *Pisidia longicornia*; its megalopae contribute greatly to the diet of fishes in the area, and the adults are prey of other crabs. No parallel situation occurs in New Zealand; the camouflage crab *Notomithrax minor* is common in some areas beneath mussel farms, but I have not observed distinctive differences between farm and non-farm areas.

Table 2. Summary of mussel farming impact studies.

Study	Location	Depth
Hatcher et al. 1994	Nova Scotia	7 m
Barranguet 1997	Mediterranean	5 m
De Casabianca et al. 1997	Thau Lagoon, France	5 m
Gilbert et al. 1997	Thau Lagoon, France	8.5 m
Souchu et al. 2001	Thau Lagoon, France	<10 m
Lawrence et al. 2000	Nova Scotia, Canada	10 m

Hatcher et al. (1994) investigated the effects of culture of *Mytilus edulis* and *M. trossulus*. They found that seasonal patterns of chlorophyll abundance correlated with sedimentation rate, and that most particulate carbon and nitrogen that fell to the seabed was not incorporated into the sediments. They reported that the most noteworthy effect was enhancement of NH_4^+ from sediments under the mussel farm.

Barranguet (1997) studied mussel *Mytilus galloprovincialis* farms in Mediterranean, where a "table" system operates; mussels are suspended from metallic structures fixed to the bottom at about 5 m depth. Mussel culture increased shell debris, and raised the redox layer via the higher organic layer. Plant pigments (chlorophyll a) were more abundant under mussel tables, but I could find no indication whether that contributed to mussel growth.

Jaramillo et al. (1992) described deposition rates of 553 g m^{-2} day^{-1} for *Mytilus chilensis* and 271 g m^{-2} day^{-1} for *Choromytilus chorus* in Chile. They summarised the results of Lopez et al. (in Spanish) who suggested that abundance of 3 crabs increased below mussel rafts. They also noted that several species have been introduced deliberately: *Haliotis rufescens*, and *Crassostrea gigas*.

3.1.2 Oysters

New Zealand

Oyster farms have effects on flow rates that may result in greater settlement of fine material beneath them (Forrest 1991). Forrest studied the sediments under oyster racks in the Mahurangi Harbour, in northeastern New Zealand, and found that sediments were generally less consolidated, finer-grained, and organically enriched. Further, sediment accumulated more at farms, and the redox potential discontinuity layer was closer to the sediment surface. The area impacted at one site was thought to extend about 30 m beyond the boundaries of the farm.

Ecological impacts of oyster farms in Mahurangi Harbour were assessed by Forrest (1991), who described increased abundances of some polychaetes. He reported rates of sedimentation of 281 and 436 g m^{-2} day^{-1} at two oyster farms in Mahurangi Harbour, and also reported that shell material was deposited under racks. Such shell deposition is shown photographically in Forrest (1994), with benthic data showing that invertebrates are more abundant under oyster racks. The caption of his Fig. 1 indicates that the more numerous individuals are derived from fewer species.

International

Kusuki (1977) described sedimentation effects of densely stocked Japanese oyster grounds. Castel et al. (1989) found that oyster parks in France produced elevated organic carbon, and seasonal anoxia. The fauna responded with an increase in meiofauna and a decrease in macrofauna. Dumbauld (1997) reviewed the effects of oyster farms on US west coast estuaries, noting differences between rack and seabed farms. Gilbert et al. (1997) noted effects of oyster *Crassostrea gigas* farming on nitrogen cycling in and near the sediments of a French lagoon. Shellfish farming lowered nitrification rates and caused dissimilatory nitrate reducing processes to be elevated. The result was that nitrogen remained available to phytoplankton as ammonium, and hence maintained productivity. Nugues et al. (1996) found a halving of macrofaunal abundance beneath oyster trestles, reduction in water flows, doubling of sedimentation rates, increased organic content of sediments, and reduction in the depth of the oxygenated layer. The extent of the impact was the immediate area. Simenstad & Fresh (1995) described spraying of oyster grounds with carbaryl to kill crustaceans, followed by harrowing. Kaiser et al. (1998), reviewing that study, suggested the effects were likely to be similar to dredging. Application of gravel changed the fauna from polychaete dominated to bivalve and nemertean dominated (Simenstad & Fresh 1995).

3.1.3 Other bivalves

In some areas of New Zealand harvesting of cockles or littleneck clams *Austrovenus stutchburyi* occurs. Aquaculture does not apply for New Zealand cockles however, some practices for maintaining areas (such as moving stock from one area of the shore to another) may be regarded as enhancement. I am unaware of published assessments of any such practices, and hence cannot review them. Instead, I briefly mention the environmental consequences of management practices for benthic environments in fisheries for other species.

Some overseas fisheries involve direct disturbance of the intertidal seabed, in order to harvest shellfish such as cockles (Kaiser 2001). The physical effect of the harvesting is usually a pit or trench, that may take some time to infill (e.g., Cotter et al. 1997, Hall & Harding 1997), and there is debate as to how long that period might be (Kaiser 2001). Studies in different areas have found widely varying results, that may relate to the physical (wave disturbance) and sedimentological characteristics of the sites. A variety of other methodological difficulties has been identified, such as the validity of scaling up from experiments done at scales of < $1m^2$ to the larger areas that are subjected to harvest, and the possible influence of disturbance during harvesting on other invertebrates and plants. Some studies exist on the effects of intertidal clam harvesting (e.g., Kaiser et al. 1996, Cotter et al. 1997, Hall & Harding 1997), but it is unknown how those results might apply to the New Zealand situation.

Kaiser et al. (1998) reviewed the culture of North American clams (*Tapes philippinarum*, *Mercenaria mercenaria*), noting that some form of habitat modification such as adding gravel and/or shell, placing protective netting over the area, or placement in “poches” is frequently done to avoid predation. Such procedures and structures may decrease the area available for natural fish feeding, by altering habitats or simply excluding fish from the seabed. Intertidal harvesting may also disturb the behaviour of wading birds. Mojica & Nelson (1993) studied the impact of hard-shelled clams on-grown in bags. They found no effect, but sample sizes were low. Spencer et al. (1996, 1997, 1998) reviewed the culture of imported Manila clam in Britain (including use of protective netting to prevent escape). The placement of plastic netting led to an increase in sedimentation rate, and subsequent domination first by spionids, then by deposit-feeding polychaetes. Netting became fouled by the green alga *Enteromorpha*, which in turn was fed on by littorinids. Another (inaccessible) study by Davies et al. that was reviewed by Kaiser et al. (1998), noted that netting could be removed and that the fine sediments would then wash away, whereas the addition of heavier material, such as shell, would persist.

3.1.4 Abalone

I could find no published studies that assessed the environmental impacts of abalone (paua, *Haliotis* spp.) culture. A very large literature deals with aquaculture of abalone, but there is minimal consideration of the impacts. As food is added to the farm, it is assumed that issues concerning nutrient enrichment would arise.

Conclusions

Aquaculture of shellfish may have important effects on the seabed. Shell, debris from the farm, and faecal pellets may reach the seabed and modify the environment. The seabed may be considerably modified by marine farming activity by the addition of shell, and the infaunal environment will be changed considerably. Few New Zealand studies have addressed such habitats, and there is very little quantitative data. This is an area that requires detailed research, especially since many marine farms are being applied for in different parts of New Zealand.

3.2 Finfish

A large international literature has focussed on benthic impacts of fish farming (summarised in Goldburg & Triplett 1997, reviewed by Gowen & Bradbury 1987, Munday et al. 1994, Gowen & Rosenthal 1993, and Wu 1995). Fish farming tends to deposit organic material on the seabed, and Wu (1995) considered that the impact of aquaculture occurred mainly on the seabed, rather than on the water column. Much of that material is either intact pellets that have not been eaten by fish, or faecal material, but other material from the farm may also be present. Pearson & Black (2001) reviewed the impacts of marine fish cage culture, emphasising the importance of site characteristics in controlling the persistence of an impact. The degree of the impact varies with species, culture method, feed type, feeding technique, and the physics, chemistry and biology of the receiving environment. Findlay & Watling (1997) usefully summarised the literature regarding effects in their Table 1.

New Zealand

Pridmore & Rutherford (1992)'s findings regarding the nitrogen budget of Big Glory Bay have been mentioned above. More recently, Morrisey et al. (2000) tested the Findlay-Watkins model regarding benthic impacts for sediments on the seabed at Big Glory Bay, Stewart Island. They described layers of material 27-43 cm or more deep below farm sites, and assessed recovery periods at 3-7 years. They also found concentrations of zinc that exceeded the criteria for adverse ecological effects, and they suggested that recovery of benthic assemblages might be delayed because of possible negative effects of heavy metals on the recruitment of invertebrates. They concluded that their usage of the Findlay-Watkins model was appropriate and useful, but also that high replication of sampling was required in the naturally heterogeneous seabeds beneath marine farms. One difference between the international literature and New Zealand studies is the greater depth of the latter (Table 3).

Table 3. Studies of fish farming and the seabed depths at study sites.

Study	**Location**	**Depth**
Holby & Hall 1991	Gullmar Fjord, Sweden	18–21 m
Hargrave et al. 1993	Bay of Fundy, Canada	12–14 m
Findlay & Watling 1997	Maine, USA	11–14 m
Kraufvelin et al. 2001	Archipelago Sea, Finland	5–11 m (?)
Karakassis et al. 1999	Greece	19 m
Katavic & Atolic 1999	Croatia	15–30 m
Johnsen et al. 1993	Norway	11–14 m
Troell et al. 1997	Chile	15–35 m
Lumb 1989	Scotland	Most <15m, all < 25 m
Ye et al. 1991	Tasmania	12 m
Yokoyama et al. 1997	Japan	14–18 m
Molina Dominguez 2001	Canary Is.	18–22 m
Cheshire et al. 1996b	South Australia	15–18 m
Morrisey et al. 2000	Stewart Island, NZ	26 m

International studies

Gowen & Bradbury (1987) considered that the spatial extent of that impact was of the order of 30 m, but that the zone of impact may extend further where trash fish is used as food (Wu et al. 1994). Furthermore, Ye et al. (1991) used stable isotopes to show that the influence of a Tasmanian salmon farm extended to 60 m from the cages, whereas effects on the fauna could only be detected to 30 m. The influence was evident as elevated organic content and alterations to taxonomic composition (including lower Shannon diversity). Hargrave et al. (1993) suggested that uptake of oxygen and release of ammonia from sediments beneath finfish cages can be 4–27 times greater than that of unimpacted sediments. Buschmann et al. (1996) reviewed salmon aquaculture in Chile, noting that most of the published studies were done at sites with large current flows. The impacts at those sites were mainly small, but differed qualitatively from those done elsewhere in that a gastropod *Nassarius gayi* became more abundant under culture units. Karakassis et al. (1998) suggested that anoxic conditions extended to 25 m from cages in Mediterranean situations.

Roth (2001) discusses the negative aspects of intensive salmon farming in Scotland, listing moratoria on expansion of salmon farming activities, relocation of farms at unsuitable sites, reduction in stocking densities, a ban on the use of chemicals, an increase in fallowing periods and spacing among farms, as being desirable, and suggesting an independent public inquiry into the environmental impacts of salmon farming. Prospects for amelioration of impacts via polyculture have been investigated. Troell et al. (1997) showed increased yields of *Gracilaria chilensis* near salmon cages, as well as improved water quality. Neori et al. (2000) discussed an integrated system for culture of fish, seaweed and abalone in Israel, whereas abalone and seaweed co-culture has been investigated in Oregon (Evans 2000).

Cheshire et al. (1996a) developed survey protocols for surveys of impacts of tuna farms near Port Lincoln, South Australia. Samples were taken with video, and a remote suction sampler, but video proved unsuitable because of low visibility due to fine sediments. Pilot studies with photorespirometer, and sediment chemistry studies were inconclusive. Benthic survey protocols for epifauna were established, but diver and video surveys provided results that were inconsistent with one another. This study emphasises the need for methodological trials of sampling techniques.

Cheshire et al. (1996b) described the findings of studies of tuna cage impacts in detail. There was a high impact area of 5-m radius round a cage, with many polychaetes, nebalids, brachyurans, and anthozoans, and intermediate numbers of ascidians, holothurians and sea urchins. Beyond that radius, at 5–20 m from the cage edge, was an area of moderate impact, where abundances of ascidians and holothurians increased, but there were fewer polychaetes and sea urchins compared to the area of primary impact. At 20–120–150 m radius there was no build-up of organic detritus, but more ascidians and holothurians. It was noted that currents were less than 2 cm / s, at depths of 15–18 m.

Hayes (1997) reviewed the southern bluefin tuna fishery. She noted that ranching had potential deleterious benthic effects, that pilchards for feed might be depleted, and that pilchards imported as feed may have been implicated in a herpes-like viral infection that affected wild populations of pilchards (see Diseases section below). Hayes (1997) reviewed information indicating administrative difficulties and debate regarding the independence of scientific advice.

Black et al. (1997) examined the impact of Ivermectin on benthic polychaetes. They concluded that Ivermectin, used to treat sea lice on Scottish cage farms for Atlantic salmon, was only likely to have negative effects at concentrations more than an order of magnitude greater than expected from a single treatment. However, there was potential for cumulative impacts, and those effects were suggested to significantly lengthen breakdown times of benthic wastes. There is a large literature on this topic, and technology to lessen benthic impacts has been developed (Ervik et al. 1994).

Buschmann et al. (1996) in their review of Chilean aquaculture, discussed the possible effects of treatment of *Gracilaria* plots with agrochemicals ("pyretroids"), and documented reductions in survival of crabs beneath the farms.

Lumb (1989) reviewed conditions at 57 Scottish salmon farms, noting that widespread acute organic enrichment and outgassing occurred. Kraufvelin et al. (2001) noted that of two sites studied 6 and 7 years after rainbow trout farming, one showed considerable improvement, whereas the other did not. They related the difference between the two sites to different circulation patterns, with the site that recovered having greater circulation. Karakassis et al. (1999) similarly followed recovery of farm sites after cessation of 6 years of finfish (sea bream and sea bass) farming. They noted that a secondary disturbance by a benthic algal bloom, following nutrient release from sediments, delayed recovery. Twenty-three months after cessation of culture, strong signals of disturbance were still present. Johnsen et al. (1993) noted that chemical signatures could be used to track the influence of salmon farming. Yokoyama et al. (1997) assessed benthic impacts of yellowtail and red sea bream (= snapper). They considered that there was evidence of a large impact of fish farming, with azoic conditions occurring at the farm site during summer and autumn. Hargrave et al. (1993) considered seasonal changes in benthic fluxes of dissolved oxygen and ammonium at Bay of Fundy sites. They noted that maximal water temperatures corresponded with maximum average ammonium release, and that, oxygen uptake coincided with sediment sulfide accumulation.

Molina Dominguez et al. (1997) described a pilot cage farm for on-growing gilthead seabream (*Sparus aurata*) located in the Canary Islands. Analyses of nutrients within the sediments below the cages over the course of the study revealed no noticeable accumulation of solid particulate wastes from the farm. They attributed the lack of effects to the high current flows, and the site was also quite deep, allowing feed to disperse widely.

Delgado et al. (1999) reviewed effects of fish farming on seagrass beds in the Mediterranean, concluding that seagrass continued to decline for 3 years after the cessation of fish farming because of the persistence of organic matter. Katavic & Atolic (1999) reviewed the impacts of cage farms for sea bass in Croatia, where floating cages occur in most semi-enclosed coastal basins. There was little effect on benthic sediments, except for evidence of oxygen depletion in summer, and beds of the seagrass *Posidonia* had regressed.

McCaig et al. (1999) gave a more detailed analysis of microbiology on seabed. PCR (polymerase chain reaction) investigations of samples from the highly polluted fish cage sediment sample was present at a lower intensity in the 20-m sample but was absent from the pristine 40-m sample station, indicating the range of impact. They suggest that a novel *Nitrosomonas* subgroup was selected for within polluted fish farm sediments and that the relative abundance of this group was influenced by the extent of pollution.

Summary

The benthic effects of fish farming are relatively well-known internationally, and have been investigated in New Zealand. Studies from overseas are moderately transferable, although New Zealand salmon farms are in deeper water than most overseas studies. Proposals to develop aquaculture of finfish species suggest that further investigations of other species may be warranted. Australian tuna cage investigations suggest quite different responses to those found for salmonids elsewhere (mainly in the northern hemisphere). I predict that the ecological effects of fish farming on benthic organisms will vary greatly among areas, and whether there might be undue adverse ecological effects is unpredictable. Given the relatively small area affected by finfish farming at present, such activities are unlikely to have important widespread effects.

4. Litter impacts

Like any human activity, aquaculture has the potential to generate rubbish. Some of that rubbish may remain onsite, some may sink to the seabed, and some may be exported from the site. There is a small amount of data concerning litter due to aquaculture, but the large litter literature does not include many mentions of aquaculture.

4.1 Shellfish

Litter from mussel farms is abundant on shores round the Marlborough Sounds (Backhurst & Cole, unpubl. data). The debris mainly comprises ties that secure mussel lines to backbones, but whole mussel floats also occur. On the seabed under mussel farms there is often rope, and droppers. Industry is undertaking monitoring to investigate sources of that litter, and the Mussel Industry Council's Code of Practice dictates that litter should be placed in bins on board barges.

4.2 Finfish

Under marine farms in New Zealand there may be items such as feed bins that have dropped over the side of the structure, and other items such as ropes.

Overall there is little published information regarding litter on New Zealand shores (but see Gregory 1999, Backhurst & Cole 2000). Backhurst et al. (unpubl.) found very high abundances of mussel ties on the shores of Crail Bay in the Marlborough Sounds, and I am aware of similar occurrences elsewhere in Marlborough Sounds. Shore clean-ups are relatively common (both organised and by the efforts of individuals), and dive clubs run underwater cleanups, but in the absence of information regarding the composition and abundance of that material, it is difficult to determine the proportion that derives from aquaculture. The mussel industry runs shore clean-ups in the Marlborough Sounds (B. Cardwell, Sanford Havelock, pers. comm.).

Much of the concern regarding litter stems from the effects it may have on wildlife, yet there are few observations to indicate whether wildlife is impacted by aquaculture debris in New Zealand. Two studies describing debris in the marine environment of New Zealand mention fisheries, but not aquaculture explicitly (Department of Conservation 1990, Smith & Tooker 1990).

5. Introduction of species with structures

There is a prominent literature regarding the negative effects of species introductions (e.g., Kaiser 2001). In New Zealand, aquaculture of introduced species occurs (e.g., Pacific oyster), and introduced species may be prominent on aquaculture structures (e.g., *Undaria*). Kaiser (2001) discusses a number of European examples where species have been introduced with international export of bivalve mollusc seed, including slipper limpets *Crepidula fornicata*, the American whelk tingle *Urosalpinx cinerea*, and introductions of diseases have occurred (the latter is dealt with in Section 10). Gaffney & Allan (1992) considered alteration in gene frequencies resulting from ecological interactions with introduced organisms, and as in many other studies of introduced species, they emphasise the poor predictability of such introductions.

Ballast water is the major potential source of introductions into New Zealand of microscopic stages of invasive species. Species are suspected to have been introduced on vessels and oil rigs brought into New Zealand waters. Aquaculture structures have not been introduced from overseas to date, but there are examples of species that have spread within the country, with aquaculture-associated activities implicated in their spread.

5.1 Shellfish

Shellfish farming, and activities associated with shellfish farming, are implicated in the spread of *Undaria.* The spores of that species appear to disperse widely, and to survive for some time on wet material, including on the hull of vessels. Transfer of materials for aquaculture among areas is therefore a possible source of spread. To date the species has spread as far north as Gisborne. A concerted eradication plan is underway at Big Glory Bay, Stewart Island. Any aquatic activity is capable of spreading *Undaria*, but the movement of boats, ropes, spat and buoys among areas poses a large risk.

5.2 Finfish

Only one marine fish species, a goby, has been introduced into New Zealand (Willis et al. 1999). That goby is thought to be associated with ballast water, rather than aquaculture structures. The goby has been found at a number of North Island harbours, indicating that it may be spreading within the country.

There is considerable biosecurity effort on introduced species at present, but the international ports are the focus of that effort. Should an aggressive invader arrive, aquaculture and activities associated with it could be a major vector for its spread.

6. Buildup of predators under and around farms

Predators of cultured stock may build up round marine farms, since they supply an abundant source of food.

6.1 Shellfish farming

Increased starfish abundance has been noted on some oyster farms (Forrest 1991) and beneath mussel farms (Cole & Grange 1996; Inglis et al. unpubl.). To what extent this represents localisation of existing populations, as opposed to recruitment from the water column and increased growth of starfish beneath the farms, is unknown. Increased abundance of starfish might simply reflect extra suitable “hard” habitat, rather than the food supply.

Mussel dropoff can affect the habitat heterogeneity for other fauna, increasing the food available for scavengers and organic material enrichment (Grant et al. 1995). Buschmann et al. (1996) noted the abundance of mussels under farms, and alluded to their effects on predators (though they supply no other information).

High abundance of spotties *Notolabrus celidotus* at marine farms is cause for concern, as they may damage crop mussels. However, Carbines (1993) studied the accumulation of spotties and other fish round mussel farms in the Marlborough Sounds, and found that most of the fish were aggregated near the mooring blocks, and that the abundance of spotties, at least on farm lines, was low. Leatherjackets *Parika scaber* were the most abundant species on the mussel lines.

6.2 Finfish farming

Predation by birds is a severe problem for finfish farmers in some parts of the world. Carss (1993) indicated that cormorants *Phalacrocorax carbo* attacked fish through the mesh on Scottish fish farms, causing severe wounding. There was a tendency for wild fish to aggregate near the fish farms and it is possible that elevated predation on wild fish stocks could occur due to this association. We could find no published information regarding impacts by birds on fish farms in New Zealand.

Predation by seals is a problem at salmon farms in some parts of New Zealand. Seals that are caught around Marlborough Sounds mussel farms are removed to the west coast, can return within a few days. Buschmann et al. (1996) considered that sea lion and seabird mortalities at Chilean marine farms needed attention. Morris (1996) reviewed predator exclusion devices with respect to the Maine salmon fishery, and concluded that a multifaceted approach would be necessary. Pemberton & Shaughnessy (1993) discussed the problem of seals at fish farms in Tasmania. They concluded that shooting (done under permit) was inefficient, and that steel mesh nets round the outside of the cages were the most appropriate response. Given the small extent of finfish farming in New Zealand at present, this is unlikely to be an issue.

7. Displacement of fishing

Aquaculture structures may force fishers that require towed gear to focus their effort more intensively in other areas. Benthic fishing techniques such as dredging and trawling are well-known for their effects on the seabed (review of Dayton et al. 1995, Probert et al. 1997, Thrush et al. 1998). It is possible that marine farm structures might either discourage dredging and trawling altogether, and thus provide some protection, or they might focus fishing effort onto other areas, resulting in more intensive benthic damage in those other areas.

7.1 Shellfish farming

Mussel farms occupy space that trawling and dredging may have previously used. Sidescan sonar surveys in the Marlborough Sounds reveal scars on the seabed that possibly relate to trawling (NIWA, unpubl.). Though farming areas remain available for fishing, recreational fishing interests routinely object to applications for mussel farming. This is usually justified on the basis of decreased access for drift fishing to areas, rather than a biological impact. Though objections to mussel farm proposals frequently cite declining fish resources close to points of access as a reason for opposing mussel farms, the simplest explanation for declining fish resources is that fishing is responsible. As mussel farms expand into other areas, these impacts may become better described.

7.2 Finfish farming

Because finfish farms occupy space, displacement effects may also occur on other fishing methods. As there are few finfish farms at present, there are few examples of such impacts.

Summary

Both positive and negative effects of displacement of fishing on a fishery may occur. Until the direct effects of aquaculture on fisheries are better described, it is unknown which (positive or negative) effects will occur. Those effects will also likely vary with the type of aquaculture, and its location.

8. Genetic impacts

Genetic impacts of aquaculture may occur at many levels. It has been known for some time that fishing effects evolutionary change (review in Hutchings 2000). There is concern that aquaculture may reduce overall biodiversity, particularly in tropical areas where mangals (mangrove forests) may be reclaimed for shrimp ponds. There are further concerns such as fertile interspecific hybrids, selected strains or genetically modified organisms. Escapes of farmed individuals may dilute the gene pool of wild individuals. Hutchings (2000: 302) states that: "Adaptation to local environments, genetic differences arising from altered selection pressures and rearing environments, outbreeding depression, and different disease / parasite profiles suggest that the frequency and intensity with which escaped salmonids enter rivers will negatively influence wild stocks ...". Allendorf (1991) considers genetic consequences of fish introductions, particularly hybridization. Gaffney & Allan (1992) review genetic impacts of aquaculture pertaining to shellfish, and also consider alterations in gene frequencies resulting from ecological interactions with introduced organisms. Smith (1990) reviews the use of gel electrophoresis for identification of Australasian fish stocks. Several methods of measuring genetic relatedness are available; Smith et al. (1997) compared three methods of assessing genetic relatedness for wild orange roughy and found that mitochondrial DNA (mtDNA) techniques detected less genetic subdivision among populations than allozymes (as measured by traditional starch gels), and random amplified polymorphic DNA (RAPD). The implication is that any one method may not reveal the full details of relatedness. Apte & Gardner (2001a) identified mDNA markers for *Perna canaliculus*, but those techniques have not as yet been used more widely.

Genetic variability is important to aquaculture in several ways. The most obvious and pressing need is to establish which species are present (e.g., Buroker et al. 1983). Genetic consistency may mean that desirable traits may be selected for by the culturist. This is mainly done for species that are closely managed throughout the life cycle and particularly at early life history stages. For example there is a large literature on phenotypic variation in chinook salmon *Oncorhynchus tshawytscha* (e.g., Kinnison et al. 1998). Quinn & Unwin (1993) showed that considerable adaptation to local conditions by *Oncorhynchus tshawytscha* had occurred within 20 generations of their being introduced. Genetic variation is the raw material on which artificial selection must act. Patterns of genetic variation and population linkage can vary greatly among closely related species; *Jasus edwardsii* in New Zealand and Australia are considered to be one population (Ovenden et al. 1992), whereas those of *J. verreauxi* (which also occurs in Australia and New Zealand) are disjunct (Brasher et al. 1992). Sin (1997) usefully reviewed transgenic fish (derived by artificial transfer of rearranged genes into newly fertilized eggs) in aquaculture. Broodstock programmes have used transgenes to produce fish with accelerated growth, tolerance to low temperature, and disease resistance. The use of techniques to transfer genes poses many problems, such as the potential for transgenes to exist outside the chromosome, and therefore to be available for incorporation into viruses.

The main issues for genetic impacts of aquaculture are: translocation, inbreeding depression, genetically-modified organisms, and interbreeding with natural populations.

Translocation

Translocation of aquacultured species may have genetic effects by introducing different genetic material to populations. This is mainly an issue for species that have limited outbreeding, limited dispersal and localised populations. One New Zealand example would be paua *Haliotis iris*, whose larvae are thought to be pelagic for 5−8 days. Another example is dredge oysters *Tiostrea chilensis* that brood larvae (see Cranfield & Michael 1989 for qualification). Such species are likely to demonstrate localised adaption to environmental conditions (see also salmon literature mentioned above). If new genomes are introduced to an area, with subsequent interbreeding, they may dilute the gene pool, reducing fitness and lead to a decline in stock size. Such effects are most keenly investigated for anadromous fishes such as steelhead (= rainbow) trout in California, where individual rivers may have their own stocks. Quinn & Unwin 1993 suggested that individual tributaries of a single river could have chinook salmon with differing life history traits. Most studies of New Zealand aquaculture species indicate large stock sizes, and little genetic subdivision (Table 4).

Table 4. Genetic studies of natural populations of New Zealand aquaculture and potential aquaculture species.

Study	Species	Genetic subdivision
Apte & Gardner 2001b	*Perna canaliculus*	No
Gardner & Kathiravetpillai 1997	*Perna canaliculus, Mytilus galloprovincialis*	
Gardner & Palmer 1998	*Mytilus galloprovincialis*	
Gardner et al. 1996a	*Perna canaliculus*	
Gardner et al. 1996b	*Perna canaliculus*	
Intasuwan et al. 1993	*Gracilaria chilensis*	2 different groupings
Mladenov et al. 1997	*Evechinus chloroticus*	No
Smith et al. 1980	*Jasus edwardsii*	No
Smith et al. 1986	*Crassostrea gigas*	No
Smith 1988	*Perna canaliculus*	Yes
Smith et al. 1989	*Paphies subtriangulata*	Yes
Smith & Conroy 1992	*Haliotis iris*	Aquaculture decreased genetic variability in hatchery vs wild
van den Enden et al. 2000	*Rhombosolea tapirina*	Aquaculture decreased genetic variability in hatchery vs wild
Candia et al. 1999	*Gracilaria*	Identification of species
Broom et al. 1999	*Porphyra*	Identification of species
Grewe et al. 1994	*Nemadactylus douglasi*	Australian fish differ from NZ ones
Sin et al. 1990	*Perna canaliculus*	Differences between intertidal and subtidal populations, and northern and southern intertidal populations.
Buroker et al. 1983	*Tiostrea chilensis and T. lutaria*	Species identification

The dependence of the greenshell mussel industry on Kaitaia spat does offer some potential for genetic effects, in that if crop mussels derived from spat gathered at Ninety Mile Beach were to consistently reproduce and survive, there would be the possibility of that genotype coming to dominate the population (see inbreeding depression section below). However, the most comprehensive surveys to date (Apte & Gardner 2001b) indicate little genetic differentiation among populations throughout New Zealand.

Inbreeding depression

What species might suffer inbreeding depression if they were aquacultured? Abalone (paua) and dredge oysters have already been mentioned as candidates for inbreeding depression. Other candidates might include seaweeds (natural dispersal ranges of germlings of large brown seaweeds *Carpophyllum* spp. and *Ecklonia radiata* have been estimated as less than 10 m, (Schiel 1988), live-bearing fishes such as seahorses *Hippocampus abdominalis* and sharks, and perhaps fishes that lay benthic eggs. Most aquacultured species, however, have widely dispersing larvae and usually eggs as well, so that local adaptation is unlikely to be a problem. Smith & Conroy (1992) advised on the number of broodstock required for paua farming.

Genetically-modified organisms

Alestroem & de la Fuente (1999) identify possible genes with commercial potential as those which control growth, disease resistance, freeze tolerance, sexual maturation, food quality and food preservation parameters. Kapuscinski & Brister (2001) identify a genetically-engineered organism as one created by extracting nucleic acids from one organism and introducing them into another organism, in a way that renders them heritable. Growth enhancement, disease resistance, freeze and cold tolerance and sterility can all be influenced by transgenic techniques. Many modified organisms and hybrids are sufficiently close to wild-type as to be ecologically competent on escape. Kapuscinski & Brister (2001) suggested that risk assessments needed to consider the issues of (1) the spread of a transgene from escaped GMOs into a natural population via outbreeding, and (2) the potential for ecological disruptions due to altered characteristics of transgenic organisms. They considered the risks of ecological disruptions from 3 further points. (1) the likelihood of the transgene spreading to wild populations via interbreeding with accessible wild relatives; (2) the establishment of wild populations of transgenic organisms via survival and reproduction; and (3) if GMOs are unable to breed in the wild, they may be able to have negative effects on wild organisms via predation, competition, etc.

Modelling studies (Hedrick 2001) indicate that transgenes could rapidly invade from GM fish into natural populations. The particular case that he considered was that of transgenic salmon, which he considered to be a potential risk to native salmon populations. Sterility via transgenesis is one possible way of ensuring minimal environmental impacts. Individual escapes of transgenic fish may not be problematic, but repeated escapes could see buildup of genes in natural populations (Maclean & Laight 2000). Those authors suggest that the most likely usage of transgenic fish in the longer term is the production of pharmaceutical proteins.

8.1 Shellfish

Smith (1988) considered genetic variation of greenshell™ mussels from six locations round New Zealand, indicating that samples from Kaipara and Tauranga were distinct from four more southern sites. There was also a difference at one locus between spring and autumn seed collected from Ninety Mile Beach. Apte & Gardner (2001b) found that greenshell™ mussels were genetically uniform throughout New Zealand.

8.2 Finfish

Anon (1999) mentioned genetic impacts of translocating barramundi among areas. Keenan (2000) considered that because of the low degree of genetic differentiation among populations of marine fishes generally there was no issue with genetic pollution.

Summary

This issue needs more detailed consideration. Although at present it is unlikely that any genetically modified species are used for mariculture in New Zealand, there is potential for declines of genetic diversity for some species.

9. Disease risk

Aquaculture may be associated with disease risk. The high densities that cultured animals and plants are held at may facilitate spread of diseases. It is possible that those diseases could spread to wild organisms, or spread to humans. The Joint FAO/NACA/WHO Study Group on Food Safety Issues Associated with Products from Aquaculture (1997) provides a comprehensive review of fish parasites and human safety. They identify trematodiases, nematodiases, and cestodiases as the major parasites that may be transmitted to humans, but the specific human diseases are generally most abundant in freshwater and tropical marine species. Bacteria that are pathogenic to humans in aquaculture species may derive from bacteria naturally present in the aquatic environment, and from those present as a result of contamination with faeces.

Table 5. Major bacterial pathogens associated with aquaculture (from Joint FAO/NACA/WHO Study Group on Food Safety Issues Associated with Products from Aquaculture (1997)).

Bacterial group	**Examples**	**NZ risk and source**
Enterobacteriaceae	*Salmonella* spp.	Risk very low
	Escherischia coli	Risk low. Associated with use of cow manure in ponds.
	Campylobacter spp.	Risk low. Associated with wastewater, poultry. Reported in some bivalves.
Vibrio spp.	*V. cholerae, V. parahaemolyticus*	Risk moderate. Associated with raw shellfish.
Aeromonas and *Plesiomonas* spp.		Risk low.
Clostridium botulinum		Risk low.
Listeria monocytogenes		Risk present if hygiene poor. Associated with processed food.
Viruses		Raw molluscs
Algal toxins		Present and widespread.

Chemotherapeutants are widely used in some areas of aquaculture, raising issues of potential environmental impacts and of potential human health implications.

A significant role for stress in causing disease outbreaks is unlikely in New Zealand due to the relatively low intensity of culture (with the exception of mussel farming). However, recent press reports of low water quality in the Bay of Islands affecting oyster farming suggest that there is potential for such impacts. Diggles et al. (2002) represents a useful summary of diseases for aquaculture species.

9.1 Shellfish

Outbreaks of disease among farmed shellfish in New Zealand are uncommon. Diseases of lobster have been noted (Diggles 2000, Diggles et al. 2000). However, densities of farmed mussels in the Marlborough Sounds and the frequency of transfer of material and vessels among sites are such that a disease outbreak might spread rapidly. Transmission of a disease to wild organisms is another possibility; most areas where marine farming is carried out have wild populations of farmed species, and of other species which are similar. For example, wild populations of Greenshell™

mussels occur on rocky shores in the Marlborough Sounds at low abundances, as do blue mussels *Mytilus galloprovincialis*. On beaches in that area pipis *Paphies australis* and *Ruditapes largillierti* may be common, and in the subtidal, *Gari* spp., horse mussels *Atrina zelandica*, and dog cockles *Glycymeris laticostata*, *Glycymeris modesta* also occur. The large populations of mussels on the seabed below farms also constitute a large host population for a disease.

Outbreaks of disease in wild populations of abalone (e.g., Alstatt et al. 1996) suggest susceptibility that has potential to be affected by, or have an effect on, aquacultured individuals. Ford et al. (2001) indicated that both filtration (1µm) and UV treatment were required to eliminate the pathogens *Haplosporidium nelsoni*, the cause of MSX disease and *Perkinsus marinus*, the cause of Dermo disease, in larval and juvenile oysters. When larger filters (150µm) were used for juvenile oysters the disease re-established. There are many similar studies in the husbandry literature, but at present the lack of recurrent, described diseases in New Zealand probably means that there is little incentive to direct funding toward such issues.

9.2 Finfish

Disease is a major problem for finfish farming in some countries. The most-publicised problem is in the European salmon farming industry (e.g., Roth 2001). As more antimicrobials are used there arises the possibility that resistance of human bacterial pathogens may increase, and that more aggressive diseases may develop from selection by the antimicrobials. New diseases appear frequently; a list of widespread diseases from aquaculture would include furunculosis, infectious pancreatic necrosis, infectious salmon anaemia (ISA), and cardiomyopathy syndrome (CMS).

The best-known impacts of disease-associated measures of aquaculture relate to environmental impacts of antimicrobials themselves, rather than the diseases. In Scotland, prophylactic measures such as Deosan Deosect, Ivermectin, and Dichlorvos have been suggested to have unanticipated environmental effects, including entering the food chain. With the high usage of antimicrobial measures, considerations of resistance have also arisen. Resistance to antimicrobials has been identified in fish in Ireland, Scotland and Japan, and the resistance may be to several antimicrobial agents. The Joint FAO/NACA/WHO Study Group on Food Safety Issues Associated with Products from Aquaculture (1997) concluded that in temperate climates the risk to public health is low, and mainly relates to direct ingestion of resistant bacteria by drinking fresh water; they are of little risk in the New Zealand situation.

The persistence of antimicrobial drugs in edible tissues may lead to allergies, toxic effects, alterations to human gut fauna, and drug resistance of pathogens in the human body. The acceptable levels of drug residues in edible tissues require maximum residue limits, which have not generally been set for aquaculture species. These authorization processes appear best established in Europe, where the EU is implementing a monitoring programme for sampling fish muscle tissue, and data from Norway, where antimicrobial usage in aquaculture is quantifiable, indicate declining antimicrobial drug use. Hormones may also be used to control reproduction, but we found no literature on such applications in New Zealand.

Snapper, salmon and yellowtail kingfish are the only marine fish that are presently or likely to be held or farmed at consequential densities in New Zealand in the 2–3 year timeframe. Effects of outbreaks of disease among these in the New Zealand situation are not well known.

10. Transmission of parasites and pests

Blanc et al. (1997) reviewed large numbers of introduced parasites for freshwater systems. They suggested that almost one hundred pathogen species were introduced in European freshwater systems. It is unclear whether the problem is of the same magnitude in marine systems, but there is some literature regarding pests and parasites in relation to aquaculture in New Zealand. As materials are frequently transferred among areas in aquaculture, there is potential for parasites and pests to be spread. The review of Diggles et al. (2002), which considers diseases of importance to aquaculture, is a substantial resource in this field.

A number of reviews have been published for various aquaculture species and parasites in New Zealand (e.g., Boustead 1985, Thulin 1989, Hine 1990, Hine & Jones 1994, Hine 1995, Hine 1996). Recent studies in Australia (St. John Crane et al. 2000) indicate that a virus found in farmed salmon was also found in wild allo-specifics. It is not known whether such viruses may spread from crop fish to wild stocks or vice versa. We have found no parallel studies have been done near aquaculture sites in New Zealand. Links between pilchard mortalities in Australia and aquaculture are not well understood (Hyatt et al. 1997, Jones et al. 1997, Whittington et al. 1997, Gaughan et al. 2000), but impacts of the mortality have propagated through the foodweb (Dann et al. 2000). Hine (1995) reviews disease aspects related to translocation of fish, which occurs frequently in aquaculture.

Although New Zealand seaweeds not cultured at present, some of their parasites and/or diseases have been described (Hay 1978, Easton et al. 1995).

10.1 Shellfish

Several parasites of farmed shellfish have been described in the New Zealand situation. The best-known of these include bonamiasis, as well as mudworms that produce blisters in oysters and mussels, and peacrabs which occur within the shells of mussels.

The best known parasite of shellfish in New Zealand is *Bonamia*; its impact and ecology is reviewed by Hine (1996). Intermittently beds of the oyster *Tiostrea chilensis* in Foveaux Strait are severely impacted by outbreaks of this widely spread species (Appendix 3 also lists studies in other countries). The ultrastructure and biology of this species has been studied in considerable detail (e.g., Hine 1992a, Hine & Wesney 1992). Patterns of infection have been described (Hine 1991), the management regime considered (Hine 1992b), and Hine et al. (1998) described a herpes-like virus in larvae of *Tiostrea chilensis*, indicating some potential for spread.

Handley (1995, 1997, 1998) considered the impact of spionid polychaetes on Pacific oysters *Crassostrea gigas*, and ways of minimising infestation. An outbreak of mortality among mussels in the outer Marlborough Sounds was linked to a virus (Jones et al. 1996), and Hickman (1978) described a pea crab and a trematode from mussels also. Some studies have been done of parasites of cockles *Austrovenus stutchburyi* (Thomas et al. 1998, Thomas & Poulin 1998, Poulin et al. 2000), but they were not focussed on the aquacultural consequences. Diggles et al. (2000) described a vibrio infection of phyllosoma of spiny lobsters *Jasus verreauxi* in culture, and considered ways of treating it.

Recently the ascidian *Ciona intestinalis* has become a pest. It over-settled on mussel lines in some parts of the Marlborough Sounds, competing with the crop. Such unpredictable settlements of species that are able to grow to a similar size to the mussels, and filter similar volumes, indicate a vulnerability in the aquaculture industry. Although such heavy settlements may reflect favourable planktonic conditions, the movement of equipment between areas renders the transport of early life history stages possible, and considerable care is required. The impact of introduced species in other systems, such as the zebra mussel *Dreissenia* in the Great Lakes (e.g., Johnson & Carlton 1996), and the clam *Pomatocorbula* in San Francisco Bay (Carlton et al. 1990) underscore the importance of monitoring for such species. Although it may act as a vector for such species, aquaculture activities also provide excellent monitoring opportunities for such species. Almost nothing is published regarding the abundant encrusting fauna that occurs on crop mussels.

10.2 Finfish

Powell & Loutit (1990) described a vibrio (*Vibrio anguillarum*) from water, sediment, macroalgae, and salmon. That species is considered to be responsible for significant fish losses in aquaculture internationally, but we did not locate reports of any major losses associated with aquaculture in New Zealand.

The best known diseases of aquacultured fishes are those of freshwater fishes, such as whirling disease (Boustead 1993), and vibrios (e.g., Wards et al. 1991). Diggles (2000) described treatments for a ciliate infesting turbot juveniles in culture. Hine (1995) considered the implications of moving fish for recreational fishing, and contrasted them with those for moving fish for aquaculture. Ghittino et al. (1989) considered New Zealand to be a possible source of a serious outbreak of anguillicolosis in Italy, as did Koops & Hartman (1989) for an outbreak in Germany.

Taxonomic studies of parasites have been done for many species. Studies of species of potential aquaculture interest include snapper *Pagrus auratus* (Roubal et al. 1983, Sharples & Evans 1993, 1995a,b,c,d, Roubal 1996), elephant fish *Callorhynchus milii* (Allison & Coakley 1973), and red cod (Featherston et al. 1979).

In northern hemisphere finfish farms (Scotland, Ireland, Norway), wrasse are used to remove parasites from salmon. That usage has arisen partly in response to the problems the industry has experienced with chemical control of parasites. Several investigations have examined the possibility of disease being spread from salmon to wrasse, and from wrasse used as cleaners to wild populations (e.g., Treasurer 1997, Gibson et al. 1998, Laidler et al. 1999). As that cleaning technique is not used in New Zealand, it is not an issue.

Roth (2000) reviewed the use of pesticides to control sea lice in salmon aquaculture. The cost of the impact of sea lice was estimated at about £45M for Norway, Scotland, and Canada alone in 1996. Ernst et al. (2001) considered the use of pesticides used to treat sea lice in New Brunswick, Canada, and concluded that there might be toxic effects over large areas from cypermethrin, although not from azamethiphos.

Conclusion

To date the impacts of pests and parasites on aquacultured species have been small, but there is the potential for large impacts, because of the ease with which some may spread. Recent experience with harmful algal blooms has raised the awareness of the industry regarding the influence of husbandry on transferral of pests and parasites. Further descriptions of the range of taxa involved, particularly for the mussel industry, would be very helpful.

11. Influences of aquaculture of wild species on their local abundance

Several modes of influence of aquacultured species might be anticipated. Escapees might remain nearby and interact with stock or disperse and interact with other species. Simple escapes may lead to elevated abundances near aquaculture facilities. Such escapes will obviously depend on the mobility of the organisms; anecdotal accounts indicate that escaped salmon may persist near farms, whereas mussels that fall off lines have no option other than to remain nearby.

11.1 Shellfish

The effects of aquaculture on the local abundance of species appears to be highly variable, and difficult to assess. For example, greenshell™ mussels are grown in huge numbers in the Marlborough Sounds, but local settlement does not appear to be particularly high. Other species may spread more readily. For example, Pacific oysters are spreading along shores of the Marlborough Sounds, and throughout Golden Bay. The role of aquaculture in dispersing oysters is unknown, but as the species is an adventive (Dinamani 1971) it seems that aquaculture could play a role at least in maintaining spawning population size. Given the limited dispersal range, elevated settlement of haliotids (abalone) near outlets from unscreened aquaculture facilities would appear possible.

11.2 Finfish

Sayer et al. (1996) summarised the environmental impacts of capture of wrasse for aquaculture, and Varian et al. (1996) indicates that there are concerns regarding sustainability of that practice. There are no such parallels in New Zealand.

Seahorses and pipefishes are potential aquaculture species that have a limited dispersal range owing to the brooding of young by the males. Internationally, concerns have been expressed regarding the level of harvesting in wild populations. Although there are small-scale operations in New Zealand, and some seahorses are sold, much of the published research is focussed on better understanding the species (Woods 2000a,b). As yet, there appear to be few environmental impacts from aquaculture for this species, one goal of which is lessening harvesting pressure on wild populations.

Carss (1990) found high abundances of saithe *Pollachius virens* outside salmonid farms in Scotland. Escaped trout from the farms, and salmon, were also captured near the farms, and were found to contain feed pellets. It therefore appears that fish may aggregate near salmon farms and feed on pellets that disperse from the farm. Fish captured at some distance from the farms also contained pellets.

11.3 Other organisms

The distance over which planktonic and adult stages of organisms disperse is the most likely determinant of whether aquaculture may influence local abundances of wild species (see Jones et al. 1999). Haliotids (paua) would be predicted to demonstrate some localised build-up via short distance larval dispersal (and the limited capacity for movement of adults). I could locate no published studies showing such a pattern, but there are sufficient land-based paua farms (and perhaps research facilities) around the coast to expect escapement of larvae to have contributed to local populations. The effects for other species with longer lives (for example snapper) and with longer larval lives, are unknown. The variable success of establishment of the brown seaweed *Undaria* in the Marlborough Sounds suggests that characteristics of the receiving environment (e.g., wave action, grazers present, sedimentation levels) will be critical.

The behaviour of individuals raised in captivity may differ from those in the wild (e.g., Schiel & Welden 1987), raising the possibility that escapees will suffer greater mortality.

Conclusion

There is considerable potential for aquaculture of wild species to impact on their local abundances. The predictability of such influences is small, and it appears that detailed knowledge of the life history of the species, and the receiving environment will be required. Such knowledge does not exist for most of the aquacultured species in New Zealand, as dispersal ranges are poorly understood, and knowledge of habitats in aquaculture areas is similarly poor.

12. Effects of harmful algal blooms

Although not necessarily an effect of aquaculture, harmful algal blooms (HABs) can greatly influence aquaculture activities such as harvesting of shellfish, and movement of spat among areas. Failure to observe precautions in relation to harvesting and spat movement could have major impacts on aquaculture. The general background to HABs in New Zealand can be found in Royal Society of New Zealand (1993), Rhodes et al. (1993), and Rhodes et al. (2001). The argument is sometimes put forward that crop species might act as canaries for the ecosystem. That suggestion only applies if the canary is the most appropriate species. The wide range of latitudes and habitats that the greenshell mussel occupies suggests that the species is very tolerant of environmental extremes, and therefore would be a poor sentinel species.

12.1 Effects on shellfish

Obvious effects of toxic algal blooms occur where the relevant symptoms affect people that consume crops. In New Zealand to date this has mainly affected wild shellfish, as in the summer 2000/01 outbreak of shellfish toxicity. Rhodes et al. (2001) summarised New Zealand HABs over the last decade, emphasising the need for early detection and methodological advances for correct identification. The important effects of toxic algal blooms on aquaculture to date have been on harvesting of crop and by restricting transport of spat between areas. Monitoring of bloom conditions permitted harvesting of crop to be done in advance of a bloom arrival in 1994. Much of New Zealand's Greenshell™ mussel industry depends on wild-caught spat from Ninety Mile Beach ("Kaitaia spat") and the 2000/01 bloom initially meant that spat could not be transported between areas. That led to (a) technological innovations to remove cysts from spat, and (b) a search for other sources of spat. There were also numerous organisational developments involving Ministry of Health, Ministry of Fisheries, and New Zealand Fishing Industry Board, and controls put in place on the transfer of material among areas.

Newspaper reports during the toxic bloom outbreaks discussed above indicate that paua *Haliotis iris* were adversely affected, by the outbreaks.

12.2 Effects on finfish

Phytoplankton blooms were linked to mass mortalities of salmon at Stewart Island and have been discussed in the benthic effects section above. Their effects on wild populations are unknown; it is possible that dense blooms could have localised effects on wild fish, but mobile species would generally be expected to avoid such areas.

Conclusion

HABs are a recurrent feature of New Zealand aquaculture in recent years. It is possible that their recurrence is merely due to improved surveillance, but their presence requires increased vigilance in order to maintain domestic and export markets. Aquacultural activities have the potential to accelerate the spread of such blooms, but they also provide increased surveillance.

13. Future Aquaculture in New Zealand

At present mussel farms are developing further offshore, leading to new navigational impacts, and possibly impacts on a different suite of species. Aquaculture of southern bluefin tuna is underway in South Australia and could develop here. Sponge aquaculture is being investigated. Aquaculture of seahorses is in a relatively good position because of the volume of research preceding development of the industry. It is possible that kina aquaculture might emerge, given the size of the resource, potential returns, and research (e.g., Barker et al. 1998). See Slaski (2000) for further discussion of finfish species.

To date, administrative authorities such as Regional Councils have funded minimal monitoring of impacts of aquaculture. It is difficult to manage an activity if there is no information, or only on relevance overseas information, regarding its effects. There is scope for considerable improvement in the management of aquacultural activities, leading to a better quality environment, with the acquisition of more information regarding the impacts of existing activities. As the biology of aquacultured species becomes better understood, impacts will become more predictable.

In most situations, the environment of aquacultural activities is poorly understood. Even in Marlborough Sounds, where aquaculture activity has occurred for an extended period, there are few data in the public domain regarding the receiving environment. Studies address the nature of aquaculture impacts, but the wider ecological scope of those impacts is difficult to assess without knowledge of the receiving environment. For example, assessments of the physical oceanography of marine farm areas have become commonplace, if not obligatory, in recent years. Techniques for carrying out assessments of both the water column and the seabed at large scales (e.g., doppler current meters, sidescan sonar, remote video) are increasingly available, and I anticipate rapid progress in this area. Biological and oceanographic modelling also have made important advances, and can contribute to planning.

The interactions between aquaculture and the environment also involve the aquaculture industry itself. Elsewhere (e.g., Smaal et al. 2001) it has become clear that responses and innovations by aquaculturists can have important consequences for the nature of impacts on the environment. As environmental conditions change, and aquacultural technology adapts, there is scope for ongoing alterations to the impacts of aquaculture. For these reasons it is important that the impacts of aquaculture be assessed in relation to the techniques of the day. For example, it is clear that the large offshore mussel farms that have been applied for over the last year require a completely different approach to those that have been dealt with hitherto. Both environmental conditions and aquaculture techniques vary over time, and regarding impacts as fixed and understood could lead to inappropriate management.

14. Conclusions

I conclude that the following items are priorities for research. Because of the scale and intensity of mussel farming, most of the urgent research should be directed toward the impacts of that activity.

1. The literature review revealed no comprehensive assessment of the potential effects of marine farming on pelagic foodwebs. Whereas site assessments routinely consider whether sufficient phytoplankton resources exist to support marine farming in an area, they typically do not examine whether the supply of phytoplankton will be sufficient to maintain other ecosystems, such as rocky reef systems, or indeed pelagic foodwebs, in the area. Further data regarding the effects of mussel farms on water clarity are required.

   The identity and fate of zooplankton that might be ingested by mussels need to be assessed. Comparisons of zooplankton composition upstream and downstream of marine farms, studies of the feeding behaviour and efficiency of mussels, the behaviour of zooplankton near mussel farms, and analyses of the fate of ingested animals, all need to be carried out. Such negative impacts of mussel farming need to be evaluated against their potential positive effects, such as the habitat afforded to spiny lobster puerulus in some areas, the settlement habitat they provide for some small fishes, and the secondary productivity contributed by mobile invertebrates on mussel droppers. This type of study needs to be undertaken in more than one area of intensive marine farming.

2. Effects of marine farming on benthic foodwebs, including fishes. Deposition of mussels to the seafloor occurs under mussel farms, yet quantitative data regarding patterns in the cover of mussel drop, the effects it has on infaunal animals, effects on sediment chemistry, and its effects on mobile animals including fishes, are spatially limited. Such data should be obtained in a number of areas, both in the Marlborough Sounds, and in NZ as a whole. An important component of this study could comprise analyses of gut contents of fishes.

   As mussel farms are established in new geographic areas, diver surveys will become less adequate as a means of assessing fish abundances. There is a need to be able to adequately assess fish stocks in different areas. Those areas should include those where marine farm structures prevent use of trawl gear.

3. Potential conflicts between aquaculture and fisheries activities exist. Recent legislation regarding Aquaculture Management Areas (AMAs) may allow those conflicts to be managed. This comprises primarily a management issue, rather than an ecological effect.

4. It is important that research effort concerning toxic phytoplankton (HABs), introduced species, and transmission of pests and parasites is maintained. All three potentially could threaten aquaculture and fisheries. Public education regarding all three is important.

5. Neither regional councils nor MFish have undertaken comprehensive assessments of the impacts of existing aquaculture to date, though approval from both is required to carry out marine farming. Because much of the public debate is fuelled by poorly informed statements that are not supported by the available data, there is a need to educate the public regarding what the impacts of marine farming are. Information pamphlets, videos, and CD-ROMs will help disseminate the information that is available (mostly summarised here), and there is an urgent need for that information to be widely available to the public. The marine farming industry would be an important participant in that education process.

6. Physical effects monitoring. There is potential for marine farming structures to modify the wave climate and have effects on shorelines. As yet these effects are poorly understood and described, but wave climate is predictable for most of the coast from models. There is scope for examination of effects of marine farms on wave climate, particularly with regard to wave focussing. Other matters regarding physical effects of marine farms that warrant attention include the effects of marine farms on currents, circulation, and shore erosion.

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