PART I

CHAPTER 11

AQUACULTURE AND MARINE MAMMALS: CO-EXISTENCE OR CONFLICT?

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INTRODUCTION

Marine and freshwater aquaculture is the fastest growing world food industry; 11% per year during the 1990s (Newton 2000). In part, this is a result of the reduction of both major and minor wild fisheries (Pauly *et al*. 2002) and an increased demand for seafood. An estimated 25% of seafood consumed is produced by aquaculture and this is set to rise to 40% by 2010 (FAO 2000). One of the justifications given for turning to aquaculture is that it will relieve the pressure on wild fish stocks, but Naylor *et al*. (2000) have produced good evidence that this will not be realised unless non-marine sources of food are found for the aquaculture industry. In addition, most finfish aquaculture produces high-grade premium products targeting the gourmet market and will not relieve food shortages in third world countries.

Marine aquaculture (mariculture) makes up about 35% of world aquaculture production (FAO 2000). It includes farming molluscs (47% of total weight of mariculture, e.g. edible and pearl oysters, mussels, scallops, abalone), finfish (8% of total mariculture, e.g. salmon, trout, tuna, snapper, yellowtail kingfish), crustaceans (1% of total mariculture e.g. shrimp, lobster) and plants (44% of total mariculture, e.g. algae and seaweed). Techniques are varied, from producing fry and spat (farming) to taking wild fish and fattening them in sea cages (feed-lotting). Feeding mechanisms are equally diverse, ranging from no supplementary feeding for most molluscs to using vegetable products, fishmeal, pellets (made from wild caught marine fish) and whole fish (e.g. pilchards to fatten tuna). Almost all operations are in sheltered coastal or estuarine waters and therefore add pressure on environments already influenced by human impacts. Even land-based aquaculture can affect the coastal marine environment through increased nutrients and pollution (Black 2001a; Paez-Osuna 2001).

Pinnipeds and cetaceans have been recorded in operational interactions (damage to gear, stock predation, fatal entanglements, etc.) and biological interactions (habitat loss/degradation, reduced wild food supply, etc.) with aquaculture (Howell and Munford 1991; Wickens 1995; Würsig and Gailey 2002). Pinnipeds (almost always the otariids, sea lions and fur seals) are responsible for most interactions with farm operations, including damage to gear and fish stocks. Occasionally baleen whales have swum into cages, causing damage (Pemberton *et al*. 1991; Kemper and Gibbs 1997). Mariculturalists estimate a loss of 2–10 million of their gross production is due to marine mammal predation (Nash *et al*. 2000) and 12% of aquaculture insurance claims worldwide are related to depredation and damage by pinnipeds (Sunderland Marine Mutual Insurance Company Lim-

Table 1 Aquaculture production (tonnes) during 1997 in the main continents/countries of the southern hemisphere. South America includes countries south of the equator. All 'marine fishes' and 'molluscs' are marine production, 'diadromous fishes' includes some freshwater production and 'crustaceans' is mostly land-based production. Source of data FAO (1999) except * which are combined from SERNAPESCA (1998) and Hernandez-Rodriguez *et al.* (2000).

	Australia	New Zealand	South America	Southern Africa
Diadromous fishes	10 618	4350	267 897*	1050
Marine fishes	2090	–	278	4
Molluscs	11 939	68 900	31 398*	3000
Crustaceans	1845	–	395 549	2548
Total	26 492	73 250	695 122	6602

ited 2000). Negative interactions for marine mammals include fatal and non-fatal entanglement, illegal and permitted killing, injuries, habitat loss or disturbance and altered ecological parameters such a predator diet and distribution.

This chapter first summarises mariculture in Australia, New Zealand, South America and southern Africa. It then reviews pinniped and cetacean interactions with finfish and shellfish aquaculture, making specific reference to seven studies (three in Australia, two in New Zealand and two in Chile). The discussion highlights ecological considerations, lessons from the northern hemisphere and recommended avenues for further progress.

MARICULTURE IN THE SOUTHERN HEMISPHERE

The Food and Agriculture Organisation of the United Nations (FAO) produces detailed statistics on fisheries and aquaculture production each year (FAO 2000). In the southern hemisphere, South America is by far the largest producer of aquaculture products (Table 1). Crustaceans (mostly shrimp) are included in the summary below because, although usually grown in land-based ponds, they can have major indirect effects on the coastal marine system. In contrast to its leading role in production, South America has been slower to document and investigate interactions and conflicts between marine mammals and aquaculture operations. Figure 1 shows where mariculture is conducted in the southern hemisphere.

Australia

Detailed reviews of Australian aquaculture are found in O'Sullivan and Dobson (2000), Newton (2000), O'Sullivan and Ryan (2001) and the Australian Aquaculture Yearbook (2001). A map showing where aquaculture is carried out in Australia has been produced by Fish Farming International (2000). In far northern Australia, the pearl oyster (*Pinctada maxima*), sometimes in benthic culture, is the most commonly farmed species, along with edible oysters (mostly Pacific oysters *Crassostrea gigas* and Sydney rock oysters *Saccostrea glomerata*) and giant clams (*Tridacna* spp.). There are some estuarine barramundi (*Lates calcarifer*) and crocodile (*Crocodylus porosus*) farms and more are planned. Interactions are reported between turtles, but not marine mammals, and crocodile farms. Anecdotal reports suggest interactions between crocodiles, sharks and barramundi

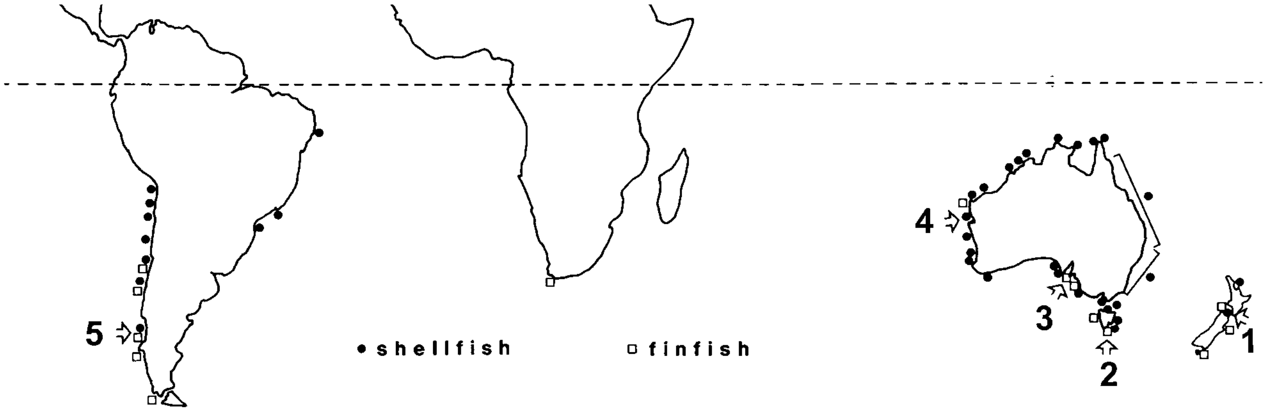

Figure 1 Major sites where marine aquaculture is undertaken in the southern hemisphere. Solid circles are shellfish, open squares are finfish aquaculture. Arrows indicate where studies referred to in this chapter are located: 1 = Marlborough Sounds, 2 = SE Tasmania, 3 = Port Lincoln, 4 = Shark Bay, 5 = 10th Region, Chile. Dotted line is equator.

farms (A. Flaherty, personal communication 2002). No pinnipeds occur in this region but there are several species of inshore dolphin (e.g. Irrawaddy dolphin *Orcaella brevirostris*, Indo-Pacific humpback dolphin *Sousa chinensis*, Indo-Pacific bottlenose dolphin *Tursiops aduncus*), as well as the dugong (*Dugong dugon*). Although there are no available reports of dugong interactions with aquaculture in Australia, entanglement is possible since mesh nets are a documented source of mortality and implicated in this species' decline in southern Queensland (Environmental Protection Agency 1999). Indirect interactions with coastal marine mammals are also likely if seagrass beds and other habitat features are affected by aquaculture, or if they are displaced through disturbance.

Shellfish production is heavy along the eastern coast of Australia where pearl oysters and prawns (mostly black tiger prawns *Penaeus monodon*, kuruma prawns *Marsupenaeus japonicus* and banana prawns *Fenneropenaeus merguiensis*) dominate in the north, and edible oysters are farmed along the central and south coast. Pilot farming for snapper (*Pagrus auratus*) has begun at Port Stephens (central coast of New South Wales) and applications have been submitted for farms in Hervey Bay, southern Queensland, a well-known locality for migrating humpback whales (*Megaptera novaeangliae*).

Mariculture in southern Australia is diverse and includes several species of finfish, edible oysters, mussels and lobster. There is intensive farming and grow-out of finfish in some areas e.g. Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) in Tasmania since the early 1980s (Figure 2) and southern bluefin tuna (*Thunnus maccoyii*) since 1992 in South Australia (Table 2). In Tasmania, salmon production is in excess of 10 000 tonnes per annum and set to double by the year 2005 (Anonymous 1999). Atlantic salmon, yellowtail kingfish (*Seriola lalandi*) and snapper are being trialed in South Australia and salmonid farming has been trialed at Albany in Western Australia. Since yellowtail kingfish are showing promise due to rapid growth rates and ability to eat pelleted food, South Australia may see a rapid expansion in this species in the near future. Polar circles (flexible sea cages hung from circular pontoons), with and without anti-predator nets, are used by all South Australian and most Tasmanian finfish farmers (Table 2). Tasmanian farmers sometimes also use box-shaped cages known as Systems Farms (Schotte and Pemberton 2002).

New Zealand

Finfish aquaculture (mostly chinook salmon, *O. tsawytscha*) was first established in New Zealand at Stewart Island in 1981 and has expanded rapidly since about 1990. It is now undertaken in three areas in the South Island, here listed from north to south; Marlborough Sounds, Banks Peninsula (Akaroa Harbour) and Stewart Island (Big Glory Cove). Finfish are grown in box-shaped, netting cages (Table 2). Anti-predator nets are used to enclose groups of cages at some sites and are planned for all sites in the near future.

Shellfish farming, particularly of mussels, is an important industry in New Zealand (Table 1). New Zealand greenshell mussels (*Perna canaliculus*), paua (*Haliotis iris*, for meat and the shell) and Pacific oysters are the main shellfish species grown but blue mussels (*Mytilus edulis*) are also farmed. Shellfish are grown at the same sites as salmon on the South Island coast (see above) as well as at Northland, Hauraki Gulf and Coromandel along the North Island coast. Mussels are grown on ropes from anchored lines, and oysters and paua on racks.

South America

Hernandez-Rodriguez *et al*. (2001) have provided a detailed summary of aquaculture in Latin America and the Caribbean, including socio-economic issues and opportunities for future development. In 1997 the value of the industry was 5.1% of total world production and was growing at 20% per year (Hernandez-Rodriguez *et al*. 2001). South America is the largest producer of both diadromous fishes and crustaceans (mostly shrimp) in the southern hemisphere (Table 1).

Almost all of the mariculture of salmonids occurs in Chile which, on a worldwide scale, is second to Norway in production levels. The industry has been operating on a large commercial scale since the 1980s and has been growing very rapidly as a result of technological improvements that took place in 1992. Over 60 companies with more than 450 concessions are currently farming salmonids with at least 4500 ha under production, yielding around 250 000 tonnes per annum (SERNAPESCA 1998). Salmon farming is important to the economy of Chile (90% of production exported, value US$970 million) and 15 000 jobs are directly related to the culture of salmonid farming. The most commonly farmed species, in their respective order of importance, are Atlantic salmon, coho salmon (*O. kisutch*), and rainbow trout (*O. mykiss*), with lesser quantities of chinook and cherry (*O. masou*) salmon.

Ecuador is the centre of shrimp farming (14% of world production) with some also grown in Colombia, as well as in Central American countries. The industry is extremely important to the Region and over 750 000 direct and indirect jobs are related to it. The main species farmed are white (*Litopenaeus vannamei*) and blue shrimp (*L. stylirostris*). The impact of shrimp farming has raised serious environmental concerns for the coastal zone, particularly mangrove forests (Paez-Osuna 2001) although with so many other anthropogenic factors operating along the coast, it is difficult to determine just how much is due to shrimp farming *per se* (Black 2001a). Disease outbreaks caused by Yellowhead, White Spot or Taura Syndrome have impacted the industry in recent years.

Table 2 Summary of aquaculture methods at localities where studies of interactions have been or are being conducted. Mitigation measures are those in place at the time of writing. Marine mammals listed are main species involved, see text for others. See text for sources of information. Asl = above sea level.

Aquaculture type/Locality	Mammal species	Commencement of aquaculture	Species farmed	Study area	Gear type	Stock food	Stock protection methods	Mitigation
Finfish								
SE Tasmania, Australia	Australian fur seal common bottlenose dolphin short-beaked common dolphin	Early 1980s	Atlantic salmon (*Salmo salar*) Rainbow trout (*Oncorhynchus mykiss*)	10 companies 30 active leases	Polar circles (diameter 20–60 m, drop 5 m) Some box-shaped cages		Anti-predator nets (10 cm mesh) Fences Railings Steel mesh	Trapping and relocation Exclusion netting Darting and removal from cages
Marlborough Sounds, Banks Peninsula and Stewart Island, NZ	New Zealand fur seal	1990 1981	Chinook (king) salmon (*Oncorhynchus tsawytsha*)	9 sites (61 ha)	Box-shaped netting cages (20x20 m) Pontoons, hung on bar, anchored	Pellets	Anti-predator nets 3 mm nylon, 21 cm mesh, 21 m drop Fences 1.0–1.25 m asl Electric fences	AHDs Seal scrammers Trapping, marking and release/ translocation
Port Lincoln, South Australia, Australia	Australian sea lion Indian Ocean bottlenose dolphin short-beaked common dolphin	1992	Southern bluefin tuna (*Thunnus maccoyii*) Yellowtail kingfish (*Seriola lalandi*)	110 cages in 2000 ~68 km^2	Polar circles (diameter 30–50m, drop 15–20m)	Mainly dead pilchards	Anti-predator nets 8-30cm mesh Railing 1m above water	AHDs
10th Region, Chile (including Isla Chiloe)	South American sea lion South American fur seal Peale's dolphin	mid 1980s	Atlantic salmon (*Salmo salar*) Coho salmon (*Oncorhynchus kisutch*) Rainbow trout (*O. mykiss*)	1997 study: 48 sites 2001 study: 23 sites	Box-shaped netting cages (15 x 15 m) often with ≥10 cages together Drop 8–20 m Some polar circles	Mainly pellets	Anti-predator nets to sea floor and/or enclose cages underneath Above water nets 1–2 m high	Legal and illegal shooting AHDs Predator models
Shellfish								
Admiralty Bay, Marlborough Sounds, NZ	dusky dolphin	1970s	Blue mussel (*Mytilus edulis*) Greenshell mussel (*Perna canaliculus*)	2 km^2	Floats (500 mm) grow lines (5 m loops) backbone lines (10–15 m apart, 100–200 m long) anchors/weights	No supplementary feeding	None	None

Table 2 Summary of aquaculture methods at localities where studies of interactions have been or are being conducted. Mitigation measures are those in place at the time of writing. Marine mammals listed are main species involved, see text for others. See text for sources of information. Asl = above sea level. *(Continued)*

Aquaculture type/Locality	Mammal species	Commencement of aquaculture	Species farmed	Study area	Gear type	Stock food	Stock protection methods	Mitigation
Shark Bay, Western Australia, Australia	Indo-Pacific and common bottlenose dolphins	Late 1980s with increase in early 1990s	Shark Bay pearl oyster (*Pinctata albina*)	221.4 ha	Suspended and benthic nylon mesh panels (~70 x 70 cm), 10-15 m apart, 100-200 m long lines	No supplementary feeding	None	None
Isla Chiloe, 10th Region, Chile	Chilean dolphin Peale's dolphin?	Early 1980s	Mainly Choritos (*Mytilus chilensis*)	Tens of sites, one of largest is over 300 ha	1 Anchored wooden floats (8 x 8 m) with suspended growth lines 2 Anchored long-lines (100 m) with floats every 2 m, 8 m growth lines every 40 cm.	No supplementary feeding	None	None

Figure 2 Salmon farming (polar circles) at Nubeena, Tasmania, Australia. Photo: D. Pemberton, July 1988.

Mollusc production in South America has concentrated on mussels, edible oysters and scallops. Chile is the major overall producer with the Chilean mussel, or chorito, (*Mytilus chilensis*) and vieras scallops (*Argopecten purpuratus*) being the dominant products. The South American brown, or rock mussel, (*Perna perna*) is mainly produced in Brazil. Chilean (*Ostrea chilensis*) and Pacfic oysters, and scallops (e.g. *Chlamys patagonica, Argopecten purpuratus*) have been farmed in Chile, Brazil and Peru. Mussels are grown on a variety of rope systems suspended in the water and hung either from float platforms or from anchored long-lines (Table 2; Figure 3). In addition to suspended ropes, lanterns and mesh bags are also used to fatten mussels and scallops. Oyster grow-out is achieved by either suspending long-lines from rafts or by placing trays on the sea floor. Mussel farming has been conducted commercially in Chile since the mid 1980s and most farming is done by local family enterprises (artesanal aquaculturists).

Seaweed culture (*Gracilaria* spp.) is underway in Chile (mostly), Peru and Venezuela. Culturing includes digging furrows in the seabed and planting stems therein.

Southern Africa

Mariculture is in its infancy in Africa (Table 1). South Africa plans to experiment with salmon farming near Hermanus (close to colonies of the Cape or South African fur seal, *Arctocephalus pusillus pusillus*) and finfish farms are being trialed in Madagascar. South Africa produces almost all of the molluscs for the region with Namibia also growing a small amount. Madagascar produces almost all of the land-bases crustaceans (shrimp) in the region.

INTERACTIONS WITH FINFISH OPERATIONS

Many of the known interactions between marine mammals and finfish aquaculture involve pinnipeds. This is because research efforts have focused on the need to mitigate seal damage. On the other hand, the short and long-term effects of finfish operations on marine mammal behaviour, ranging, demography, and ecology remain virtually unexplored.

Pinnipeds

Interactions between fur seals and sea lions, and finfish farms are numerous (Table 3) and often result in much economic loss to

Figure 3 Mussel harvesting (*M. chilensis*) long-lines in Bahia Yaldad, southern Isla Chiloe, Chile. Photo: S. Heinrich, January 2002.

the industry in the southern hemisphere (Oporto *et al.* 1991; Pemberton and Shaughnessy 1993; Sepulveda 1998; Schotte and Pemberton 2002). There have been many attempts to solve the problems but with varying degrees of success (see Mitigation methods, below). There is almost no information on the long-term and overall effects of these interactions on the pinnipeds. It is important to note that the nature of interaction varies with species of pinniped and that these animals are complex and adaptive predators. Efforts to mitigate interactions must accommodate this.

In Australia, salmonid farming, and to a lesser extent tuna feedlotting, have experienced extensive damage as a result of pinniped interactions (Pemberton and Shaughnessy 1993; Pemberton 1989, 1996). In the early 1990s the estimated loss to the Tasmanian salmon industry was AUD$10 000–175 000 per farm per annum. Interactions were reported to have begun about four years after the industry was established and involved direct predation of farmed fish stocks, loss of fish through torn nets, purported reduced feeding rates of fish due to stress associated with seal presence, entanglement and, in a single case in 2000, injury to personnel. The interactions were almost entirely due to adult and sub-adult male Australian fur seals (*A. pusillus doriferus*) (98% of all cases where species identity was confirmed). Attacks took place at night and on all sizes of fish. The fur seals made repeated attempts to access dead and live fish by breaking a hole in the nets (most were less than 200 mm in diameter). Charges of up to 50 m enabled the fur seals to push the anti-predator net against the cage net. Another technique is for the seals to use their positive buoyancy to lift the anti-predator net up to the main net then grab the main net and corkscrew until a hole is made. Nets of 4 mm braided polythene or steel mesh were not damaged. When fences extended less than 1.5 m above sea level, New Zealand fur seals (*A. forsteri*) could gain access by scrambling over the fence. Soon after the inception of the industry, the number of interactions differed markedly between and within sites and companies (Pemberton and Shaughnessy 1993). The vulnerability of fish farms to seal attacks increased sharply at farms closer than 20–30 km from Australian fur seals haul-out sites. For instance, a fish farm 20 km from a fur seal haul-out site was predicted to suffer 10 times as many attacks as one 40 km away. After industry expansion in the mid 1990s this effect diminished and distance from haul-out ceased to influence number of interactions. Currently, the only area where fish farms experience few seal interactions is at Macquarie Harbour, on the west coast of Tasmania. Other species of pinniped have also been recorded interacting with the farms, i.e.

Table 3 Demonstrated negative pinniped interactions with aquaculture in the southern hemisphere.
? means that the interaction has not been demonstrated equivocally or that species identification is in question.

Species	Fatal entanglements	Non-fatal entanglements	Illegal killing	Gear damage	Fish stock loss
Australian sea lion	Tuna feedlots	–	Tuna feedlots	Tuna feedlots	Tuna feedlots
South American sea lion	Salmonid farms	Salmonid farms	Salmonid farms	Salmonid farms	Salmonid farms
South American fur seal	Salmonid farms	Salmonid farms	–	Salmonid farms	Salmonid farms?
New Zealand fur seal	Tuna feedlots? Salmonid farms	–	Salmonid farms	Salmonid farms	Tuna feedlots? Salmonid farms
Australian fur seal	Salmonid farms	–	Salmonid farms	Salmonid farms	Salmonid farms
Southern elephant seal	Salmonid farm	–	–	–	–
Leopard seal	Salmonid farms	–	–	–	–

fatal entanglements of two leopard seals (*Hydrurga leptonyx*) and one southern elephant seal (*Mirounga leonina*).

A range of mitigation methods has been used by finfish farmers in Tasmania (Pemberton 1989; Pemberton and Shaughnessy 1993; Schotte and Pemberton 2002). In the past, shooting, emetics (lithium chloride), Acoustic Harassment Devices (AHDs) (10 or 28 kHz), seal crackers (under water explosives), electric fencing, chasing with boats, and frightening with bright lights were attempted (Table 2) but with little success in the long term. In the late 1980s government shooting permits resulted in about 100 seals being killed annually. Methods in place in Tasmania at present are trapping and relocation (under strict protocols) and anti-predator nets, exclusion. The recommended methods of reducing pinniped damage are exclusion fences, reduced access to dead fish and immediate burial of offal (Pemberton 1989; Pemberton and Shaughnessy 1993).

Capture and relocation of pinnipeds interacting with the Tasmanian salmon farming industry has been the subject of a Tasmanian study (Hume *et al*. in press). Between 1990 and May 2000, 353 animals were trapped on 672 occasions (98% Australian fur seal). Of these, 52% were trapped on at least one subsequent occasion and some were caught several times in one year (e.g. 14% two times 6%, three times 5%, four times). Some animals appeared to become habituated to being trapped at farms (e.g. one animal was trapped 43 times in four years). The number of trapping occasions varied between years, with many more relocations in 2000 (n = 472) than in 1999 (n = 56). Between February 2000 and March 2002 eight seals are known to have died in the traps or during relocation (R. Gales, unpublished data)

Mortalities of Australian fur seals have been frequently reported since 1998 (Table 4). They occurred either in the anti-predator nets or when the seals became trapped between this net and the cage net, sometimes when nets were poorly hung. Dead seals that were floating between the cage and anti-predator nets were considered to have been ‘entangled’.

At Port Lincoln in South Australia, pinniped interactions have also been recorded at tuna feedlots (Pemberton 1996). Anecdotal reports describe seals sitting on the pontoons of the polar circles (nets hung from circular pontoons) and leaping over the top of the fence. Knowledgeable observers report that these are mainly Australian sea lions (*Neophoca cinerea*) and occasional New Zealand fur seals. Almost all (89%) of the carcasses retrieved in the Port Lincoln area since feedlotting began, as well as the two documented entanglements (Kemper and Gibbs 1997), have been sea lions (Figure 4). When Pemberton (1996) reported on the interactions with tuna feedlots, he believed that

Table 4 Number of fatal entanglements of pinnipeds and cetaceans in salmonid farms in south-easternTasmania.
Source of data: Nature Conservation Branch, Department of Primary Industries, Water and Environment, Tasmania.

Species	Pre 1998	1998	1999	2000
Australian fur seal	–	2	4	30
New Zealand fur seal	1	–	–	–
Leopard seal	2	–	–	–
Southern elephant seal	–	1	–	–
	–	–	–	–
Common bottlenose dolphin	2	1	1	1
Short-beaked common dolphin	–	1	2	1

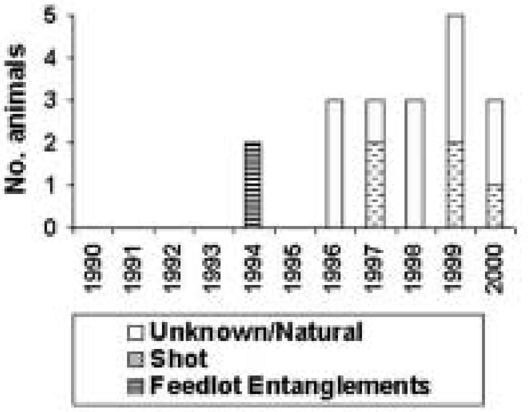

Figure 4 Pinniped carcasses from near Port Lincoln, South Australia during 1990 to 2000. All records were Australian sea lions, except two New Zealand fur seals that were diseased or starving. Shootings were confirmed by projectile retrieval. Tuna feedlotting began in late 1992.

the following characteristics of anti-predator nets were problematical for entanglements of both pinnipeds and cetaceans: too large a mesh size; holes not repaired; nets not enclosed at the bottom; nets often loose and baggy; inappropriate feeding practices (shovelling frozen pilchards) that encouraged marine mammals to visit the cages. Some of these were also likely reasons for pinnipeds gaining access to the cages and killing or damaging tuna. In addition, there were problems with animals getting over the top because fences were not high enough above the water or poorly maintained and the pontoon design acted as a platform from which the animals could launch themselves into the cage. Probably in response to a report (Kemper and Gibbs 1997) concluding that anti-predator nets were one of the factors involved in marine mammal entanglements, the use of predator nets has substantially been reduced. Anecdotal information suggests that interactions with pinnipeds began about four years after feedlotting began (Pemberton 1996).

Mitigation measures suggested by Pemberton (1996) include regular maintenance of all nets to reduce billowing and holes, extending the fences to 1.5 m above water level, cleaning up oil slicks and dead fish around the cages, enclosing the anti-predator nets at the bottom and using smaller mesh size (e.g. 6 x 6 cm) for anti-predator nets. Dumping fish factory waste into the sea at Port Lincoln has been reduced since Pemberton (1996) reported on mitigation measures to industry (C. Cartwright, personal communication 2002). The use of 1.5 m electric fences around tuna feedlots has been apparently successful in deterring pinnipeds since the late 1990s. In addition, tapering the sides of the holding cage and weighting the circumference of the floor has resulted in taut cages with a flat bottom, well off the sea floor (D. Ellis, personal communication 2003). Acoustic deterrents were found to be of little use in the long term.

The number of attacks by pinnipeds at Port Lincoln may be related to the proximity of the feedlots to the second largest breeding colony of the Australian sea lion at Dangerous Reef, about 25 km to the east. This colony had a pup production of 406 during the 1999 season, when pup mortality was 40.6% (Shaughnessy and Dennis 2000). Colony size is estimated at 1500–2000 animals (based on multipliers provided by Gales *et al*. 1994). Aquaculture zoning regulations are under review at present and may allow farms to be sited closer to this colony. The nearest New Zealand fur seal colony is about 60 km away at Neptune Islands and it had a population of between 21 000 and 27 000 animals in the summer of 1999/2000 (Shaughnessy and McKeown 2002).

In New Zealand, salmon farms in all three regions (Table 3; Figure 1) have experienced interactions with New Zealand fur seals and studies on these began in 1994. The seals damage the cage nets, allowing stock to escape, and enter cages and harass and eat the fish. They have established new haul-out sites near some farms. The estimate of damage is NZ$2 million per year. Illegal shooting of fur seals has occurred. Various mitigation methods have been attempted including Acoustic Harassment Devices (AHDs see below), tuna bombs, trapping and relocation and electric fences. The most effective method appeared to be electric fences on the farm structures because this technique resulted in a 75% reduction in seals jumping onto the structures to gain access to the pens. Anti -predator netting is presently used only at the Marlborough Sounds where it appears to be effective at reducing damage at protected farms resulting in the fur seals moving to less protected farms. Applications to translocate seals from Marlborough Sounds were declined by the New Zealand Government. There have been no recorded entanglements of seals or dolphins in the anti-predator nets, perhaps because they are enclosed at the bottom and made of stiffened nylon.

In Chile, interactions between the South American sea lion (*Otaria flavescens*) and finfish farms began when the industry was established in the mid-1980s (Table 2). The South American fur seal (*A. australis*) also occasionally interacts with farms. Sepulveda (1998) found in her one-year study that around 90% of the 48 salmon farms under investigation in Chile reported attacks by sea lions. The main mode of attack was to push against the net, enabling the sea lions to grab the fish and either damage or kill and consume them. Sea lions also damaged the nets leading to an unknown number of salmon escaping from the cages. The frequency of interactions increased in autumn and winter and nearly 80% of attacks occurred at night. The number and frequency of attacks by sea lions varied between farming centres, probably reflecting the distance to the nearest sea lion colony and the size of the salmon farm. In the 10th Region, Chile, where 85% of the fish are farmed, 24 breeding and 11 haul-out sites of South American sea lions have been recorded (Oporto *et*

Table 5 Demonstrated (or strongly suspected) negative interactions of cetaceans with aquaculture in the southern hemisphere. ? means that the interaction has not been demonstrated equivocally or that species identification is in question.

Species	Fatal entanglements	Illegal killing	Non-fatal entanglements	Habitat disturbance	Gear damage
Short-beaked common dolphin	Tuna feedlots Salmonid farms	Tuna feedlots?	–	–	–
Common bottlenose dolphin	Salmonid farms	–	–	–	–
Indo-Pacific bottlenose dolphin	Tuna feedlots	Tuna feedlots?	–	Pearl oyster lines Tuna feedlots?	–
Dusky dolphin	–	–	–	Mussel farms?	–
Peale's dolphin	Salmonid farms	–	–	Salmonid farms? Mussel farms?	–
Chilean dolphin	–	–	–	Salmonid farms? Mussel farms?	–
Bryde's whale	Mussel farm	–	–	–	Mussel farms
Minke whale	Salmonid farms?	–	–	–	–
Humpback whale	–	–	Tuna feedlots	–	Tuna feedlots

al. 1996). The estimate of total population at these sites was 31,000, which was 26% of Chile's total sea lion population.

Based on her data from the subset of farms studied, Sepulveda (1998) estimated a total loss of 3400 tonnes of salmon biomass due to sea lion attacks in the 10th Region in 1997. This was equivalent to a loss of around US$8.5 million. Brunetti *et al*. (1998) added investment and maintenance costs for anti-predator measures (nets, acoustic devices etc.) to the direct and indirect losses of salmon biomass and derived a total loss to the entire industry of about US$21 million annually.

Of the five techniques used for mitigation against South American sea lions (Table 2), only anti-predator nets have shown some success. These are made out of 2–3 mm thick nylon multifilaments with mess sizes ranging from 25 to 50 cm. The most commonly used type, of the four used, is wrapped around the entire box-type salmon cage. Net efficiency is hampered when tension is slack or the anti-predator net is moved too close to the stock cage net allowing sea lions to reach the salmon (Sepulveza 1998). Jump nets are installed about 1–3 m above the water to prevent sea lions from getting onto the platforms and entering the cages from above. AHDs have been installed at about 12% of farms in Chile (Oporto *et al*. 1991). Acoustic devices resulted in, at best, only short-term deterrence of sea lions because the animals became habituated and continued their attacks (Oporto *et al*. 1991; Sepulveda 1998). Visual models of predators (e.g. killer whales, *Orcinus orca*) have also been used but failed to deter sea lions in the long term (Sepulveda 1998).

Claude and Oporto (2000) estimated that at least 5000 to 6000 South American sea lions were shot, most illegally, during the 1980s and 1990s and they suggested that this reduced some local sea lion populations substantially. The shootings occurred at sea lion colonies as well as fish farms. The Chilean National Fisheries Service issues permits to kill sea lions that are known to cause problems but in some cases the number on the permit exceeds the estimated number of sea lions thought to be resident in the area (Oporto *et al*. 1991). Sea lions have also been killed or injured by clubbing and poisoning. Fatal entanglements are frequent for South American sea lions and occasionally for South American fur seals (Oporto *et al*. 1991) and occur in both the anti-predator nets and the nets of the holding cages. Sea lions have also been observed with debris discarded from the finfish farms around their necks (C. Morgada, personal communication).

Cetaceans

In contrast to the literature on pinniped-aquaculture interactions, that tends to focus on damage by pinnipeds, the cetacean literature focuses on negative impacts of aquaculture on cetaceans. Well-documented, negative interactions with finfish farms have been reported for dolphins and baleen whales. The most serious, in terms of the reported number of instances and possible threat to local populations, are entanglements of short-beaked common dolphins (*Delphinus delphis*), common bottlenose dolphins (*T. truncatus*) and Indo-Pacific bottlenose dolphins in anti-predator nets of finfish farms in Australia (Tables 4 and 5). An unknown number of entanglements of Peale's dolphin (*Lagenorhynchus australis*) have been reported in anti-predator nets from southern Chile (Oporto and Gavilan 1990).

Over a seven-year period (1994–2000) of southern bluefin tuna feed-lotting at Port Lincoln, South Australia, 29 fatal entanglements of Indo-Pacific bottlenose and short-beaked common dolphins were reported with many more probably having occurred (Kemper and Gibbs 2001). Most reported cases were in large-meshed (>15 cm), anti-predator nets and the study recommended either not using these nets or reducing the mesh size to less than 8 cm. Studying the carcasses of collected animals revealed that many juveniles and young, sexually mature dolphins died. Although sample sizes were small, most of the mature females were pregnant or lactating. Since the population sizes of Indo-Pacific bottlenose and short-beaked common dolphins are unknown in the Port Lincoln region, the effect of the mortalities on the populations could not be determined. Analysis of stomach contents suggested that the dolphins were attracted to the vicinity of the feedlots because of the abundant wild fish living around the farms. The study, therefore, recommended that steps be taken to reduce waste food for tuna. Other recommendations were consistent with those that Pemberton (1996) considered essential for avoiding pinniped entanglements (see above).

Another case is that of fatal entanglements of common bottlenose and short-beaked common dolphins in salmon farms in south eastern Tasmania (Table 4). Anti-predator nets were again involved in most cases, although one carcass was found floating on the lease and one between the anti-predator and fish cage. Anti-predator nets that were not enclosed at the bottom may have been responsible for some entanglements because dolphins could become trapped between the main and anti-predator nets. Entanglements typically occurred in anti-predator nets having mesh sizes greater than 6 cm. Until 1998, entanglements were rarely reported (only two common bottlenose dolphins in 1989), but lack of reporting does not necessarily mean no entanglements. In recent years reporting rates and obligations have improved and so give the impression (perhaps falsely) of increased rate of entanglement.

Baleen whale interactions with finfish farms have been reported for the southern hemisphere. In 1993, a humpback whale broke through the walls of a tuna feedlot at Port Lincoln and was trapped in the cage for about two days (Kemper and Gibbs 2001). It was successfully released without the loss of any tuna. In Tasmania, a large whale collided with the side of a salmon cage (Pemberton *et al*. 1991), probably after becoming entangled in anchoring lines. The identity of the whale was not confirmed but it was believed to be either a southern right whale (*Eubalaena australis*) or a humpback whale (Pemberton, unpublished data). Claude and Oporto (2000) mentioned that minke whales (*Balaenoptera acutorostrata*) may have been interacting with finfish farms in Chile.

Positive interactions between cetaceans and finfish aquaculture have yet to be demonstrated, perhaps because they are harder to quantify. The increased nutrients around finfish farms can lead to abundant wild fish stocks which are then available to dolphins (Kemper and Gibbs 2001). However, excess nutrients can result in environmental damage, including harmful algal blooms (Hallegraeff 1997) and changes to the benthic fauna (Cheshire *et al*. 1996).

INTERACTIONS WITH SHELLFISH OPERATIONS

Pinnipeds

To our knowledge, no interactions between pinnipeds and shellfish aquaculture have been reported. Shellfish are not known to be included in the diet of southern hemisphere pinnipeds. Possible interactions could include human activities causing disturbance near breeding colonies and feeding sites, altered marine food chains/habitat due to fouling the water and changes to the benthic fauna or wide-scale perturbations resulting in harmful algal blooms (Black 2001a).

Cetaceans

There are few documented cases of interactions between cetaceans and shellfish farms. Except for cases of entanglement in lines or collisions with gear, such interactions are likely to be subtle in nature and thus harder to quantify. Three studies in progress are beginning to shed light on how dolphins might interact with shellfish aquaculture.

At Shark Bay, Western Australia, ecological and behavioural studies of bottlenose dolphins (*Tursiops* sp.) have been underway since 1984. As elsewhere, aquaculture leases in Shark Bay are concentrated in shallow inshore waters. These habitats are important for resident bottlenose dolphin females because the use of shallow water predicts higher female reproductive success compared with deep water (i.e. >7 m) (Mann *et al*. 2000). Consequently, displacement from such habitats could have deleterious effects on female reproduction. In the core study area, one pearl oyster (*Pinctada albina*) lease became the subject of recent study. Dolphin mothers and calves did not use the pearl lease area (221.4 ha), but used an area adjacent to it (Mann and Janik 1999; Watson and Mann 2002). When illegal pearl oyster lines were set up in the adjacent area in 1999 (286.5 ha), the dolphins' average observed distance from the pearl farm was significantly greater when pearling was underway (Watson and Mann 2002). The illegal extension of the pearl lease was significant because it served as a blind experiment; dolphin researchers were unaware of the placement of new lines (no surface buoys or other cues) until The Department of Fisheries removed them about eight months later. Anecdotal data are consistent with the observed pattern. Females and calves often change course by several hundred meters, apparently to avoid swimming through the lines, although other members of the group, such as juveniles, swim through (J. Mann, unpublished data). More research is needed on why dolphins avoid the pearling areas and whether this holds for specific age or sex classes.

At Admiralty Bay, Marlborough Sounds, New Zealand, the dusky dolphin (*L. obscurus*) is being studied in relation to mussel farms (Markowitz *et al*. 2002). Preliminary observations suggest that the dolphins avoid the mussel leases, which are near the beach on one side of the bay. Since dusky dolphins have been

Table 6 Mitigation methods for reducing predator damage and entanglements in finfish aquaculture in the southern hemisphere.

Those listed under 'Not recommended' are considered not useful, by the authors, in the long term. Those with * are in Pemberton & Shaughnessy (1993), those with ^ are in Schotte and Pemberton (2002) and those with # are in Sepulveda (1998). Other methods are those recommended by the authors. + except for solution to immediate problems such as structural repairs to be done quickly.

Recommended	Not recommended
Semi-rigid or well-tensioned net material*#	Acoustic devices*#
Net mesh size 6 cm^	Shooting*#
Jump fences at least 2 m #^	Trapping and relocation+
Buffer distance of 1.5 m between anti-predator and main net #	Imitation killer whale sounds
Minimise food wastage	Emetics
Site farms >20 km from pinniped haul-out sites or colonies*#	Visual predator models #
Use pelleted food	Chasing
Remove dead caged fish immediately	Seals crackers
Repair damaged nets immediately	
Hazing*	
False bottoms on nets^	
Spectra or dyneema framleinge net material^	
Insert separation pole between main and predator nets	
Main net tapers >10%	

observed using a near-shore foraging technique in sloping shallows where there are no mussel farms, it is possible that placing the leases near the shore could interfere with the foraging behaviour of this species. Large areas of proposed mussel leases, if approved, may remove most of coastal habitat for dusky dolphins in Admiralty Bay. Other marine mammals (e.g. common bottlenose dolphin, Hector's dolphin *Cephalorhychus hectori*, New Zealand fur seal) occur in the area but the effects on these species are not known.

There are concerns about the effect of mussel farming on Chilean dolphins (*C. eutropia*) and possibly Peale's dolphins at Isla Chiloe, Chile. One of the bays, Bahia Yaldad, most frequently used by about 30–40 Chilean dolphins has become almost completely covered with mussel lines (Figure 3). These dolphins have been observed feeding close to the mussel lines but not between them and could be excluded from large parts of important foraging habitat. The bay is also known to be a fish nursery and attracts large numbers of various species of cormorant, tern and gull. Recently, lower yields of mussels have been reported in the bay (H. Blanco Paves, personal communication), possibly as a result of decreased nutrients. Despite a licensing system for mussel farms, the area appears oversaturated with lines and this may have an impact on the local dolphin populations. In addition, three large salmon farms operate within 1 km of the mussel farm complex in Bahia Yaldad. These different aquaculture operations may have synergetic effects and might exacerbate potential impacts on the ecosystem.

Positive interactions between dolphins and shellfish aquaculture have been suggested but not demonstrated. Bottom culture uses floating and platform racks on which oysters and mussels are grown. These may act as artificial reefs and have an associated fish fauna that provides prey for dolphins. Anecdotal information from New Zealand suggests that dolphins may feed on schooling fish near some mussel farms. Increased nutrients may also be beneficial to the food chain, provided that they are not in excessive amounts. However, these hypotheses have yet to be tested.

The only reported example of a baleen whale interacting with shellfish aquaculture in the southern hemisphere is that of a Bryde's whale (*B. edeni*) that died after becoming entangled in mussel lines at Great Barrier Island, New Zealand (Seafood New Zealand 1996). As humpback and southern right whales increase in numbers and aquaculture expands, there are likely to be more cases of entanglement in the ropes and lines used in shellfish operations.

MITIGATION METHODS

Experience in Australia and in other countries indicates that interactions between marine mammals and finfish farms should be considered as inevitable. They have a detrimental effect on both the marine mammal and the aquaculture industry. At present, the best methods for minimising attacks is by appropriate net design, constant vigilance, appropriate feeding regimes, site placement and gear maintenance (Table 6).

Most of the reports and workshops on marine mammal interactions held to date have been stimulated by the need to find solutions to the problems caused by predators (particularly pinnipeds and sharks) at finfish farms. For the southern hemisphere, mitigation reports are available only for Australia and Chile (Pemberton 1989, 1996; Pemberton and Shaughnessy 1993; Marine Animal Interactions Working Group 1998; Sepulveda 1998; Schotte and Pemberton 2002). Many reports and workshop proceedings are available for the northern hemisphere, including Ross (1988), Howell and Munford (1991), Reeves *et al*. (1996), Fraker *et al*. (1998). Recommendations on how to minimise or eliminate cetacean interactions with aquaculture have been addressed in few studies (e.g. Mate and Harvey 1987; Jefferson and Curry 1994; Pemberton 1996; Gulf of Maine Aquaculture-pinniped Interaction Task Force 1996; Reeves *et al*. 1996; Marine Animal Interactions Working Group 1998; Kemper and Gibbs 2001). For pinnipeds, mitigation measures can be defined as modifying practices and/or equipment in order to reduce interactions. They may be lethal or non-lethal in nature.

Gear modification

It is generally agreed that minimising pinniped damage to fish stock and gear is best done by providing a physical barrier to these adaptable and persistent predators (Table 6). The mitigation measure must be tailored to the behaviour of the pinniped species in question and should be under continual review. Fraker *et al*. (1998) discussed the many options how to reduce pinniped interactions in western North America (where box-shaped salmon cages are used) and recommended that semi-rigid materials and well-tensioned cages be used. Good diagrams of example systems were included in that report. If anti-predator nets were to be used, they would be most effective around each primary cage. In Australia, trials are currently underway to test rigid materials such as galvanised or stainless steel wire mesh and initial results are promising if the material lasts in excess of five years (Schotte and Pemberton 2002).

Polar circles are almost universally used for finfish farming in south eastern Australia. Schotte and Pemberton (2002) developed a detailed engineering approach to the study of predator damage to salmon and tuna held in polar circles. They concluded that there were inherent design problems with polar circles in that the vertical walls and horizontal floor of the net could not both be tensioned sufficiently because the polar circle framework limits the stress tensioning regime of the nets. They went on to point out that a cone-shaped net could be more universally tensioned. Additional weaknesses of polar circles were: 1) low tension through the base of the nets and 2) insufficient buffer zones between the fish stock and anti-predator nets at the sides and base when using flexible netting materials such as nylon and polyester. To increase the buffer distance to the recommended minimum of 2 m, an additional pontoon ring must be added to the existing one so that the anti-predator net could be hung at a sufficient distance from the cage net. Future cages should install pipe collar stanchion spacers to achieve the 2 m distance. Other recommendations were: 1) install a false bottom in the main net to prevent easy access by the predators to dead fish, 2) apply a minimum weight of 2.4 Te on anti-predator nets, 3) install jump fences of at least 2 m to stop pinnipeds gaining access to the cages from above, 4) use anti-predator nets made of 210 ply and with an on-the-bar size of 6 cm. Schotte and Pemberton (2002) noted that more research needs to be carried out on cage and anti-predator net materials.

Capture and relocation

The Tasmanian experience suggests that trapping and relocation offers short-term relief to farm operations (Hume *et al*. in press). This form of mitigation, however, does not provide long-term answers to pinniped interactions. Despite the high cost of moving the problem seals (AUD$650 per animal) the aquaculture industry continues to request the program.

The efficacy of trapping and relocation in Tasmania has been queried by some sectors of the Australian community and industry. The practice and procedures are conducted under the management of the Tasmanian wildlife authority. It has implemented stringent protocols to ensure provision of animal welfare considerations with animal ethics committee scrutiny and approval, including issues relevant to disease transmission (blood samples are obtained from a sample of seals each year to screen for tuberculosis, morbillivirus and brucellosis). The artificial movement of large numbers of predominantly male Australian fur seals from the south to the north of Tasmania has led to claims of increased interactions between pinnipeds and wild fisheries in waters off the north of the State. However, satellite tracking of relocated animals suggests that these claims are probably unfounded. Tracked seals have returned to seal haul-outs en-route to the south of the State. Most seals (74%) which are re-trapped at fish farms in southern Tasmania are caught at the same farm as their previous capture (Hume *et al*. in press).

Acoustic devices

AHDs have been a popular method of attempting to deter pinnipeds from finfish farms. These are sound generating devices that use a combination of intensity and frequency which is aversive to marine mammals and aims to keep them away from an area or a structure (Reeves *et al*. 1996). They are high-amplitude devices and should not be confused with ‘pingers’, which are of lower amplitude and are used to prevent bycatch of cetaceans in some fisheries. AHDs are also referred to as Acoustic Deterrent Devices (ADDs).

Some of the points made at the workshop held in March 1996 at Seattle on the use of acoustic deterrents in the conservation and management of marine mammals (Reeves *et al*. 1996) are summarised here. Acoustic devices cannot be expected to provide complete protection to finfish farms; failure may result from improper maintenance or deployment of the equipment or because the sound is not particularly aversive to pinnipeds. For example, the area to be protected may be too large, and the intensity of the received sound may be considerably less than that of the source; transmission loss is affected by distance, water depth, bottom composition and slope, water temperature and salinity. The area being protected is considerably less for an array of AHDs that is omnidirectional rather than unidirectional. Although it is important to measure the strength of the received signal at several places in the area to be protected, this is rarely done. The most successful AHDs have used sound levels with an intensity close to 200 dB re 1 μP at 1 m. This is likely to be close to the sound intensity that will cause hearing impairment in pinnipeds. Such technology has been reported as successful in deterring harbor seals (*Phoca vitulina*) at finfish farms in Maine, USA (Gulf of Maine Aquaculture-pinniped Interaction Task Force 1996) but not in the Bay of Fundy, Canada, where the AHDs produced 162 dB re 1 μP (Jacobs and Terhune 2002). It should be noted that harbor seals are phocids, whereas those attacking finfish farms in the southern hemisphere are mostly otariids. Sound should not be the primary means of keeping seals away from fish farms; the recommended procedures listed in Table 6 should be considered before AHDs are deployed. It should be noted that there are several serious negative effects of AHDs, including the likelihood of affecting non-target species in the area, such as cetaceans and possibly fish (Reeves *et al*. 1996; Morton 2000; Culik *et al*. 2000). Along the coast of British Columbia, Canada, sightings of Pacific white-sided dolphins (*L. obliquidens*) and killer whales declined after AHDs (10 kHz, 194 dB re 1 uPa @ 1 m) were introduced to keep harbor seals away from finfish farms (Morton 2000; Morton and Symonds 2002). There is also the likelihood of causing permanent hearing impairment in the target and non-target animals if the time of onset of the sound is too brief.

Most attempts to use AHDs to reduce interactions between pinnipeds and finfish farms have been based on trial and error (Pemberton 1989; Jefferson and Curry 1994). There is a need for carefully designed experiments if AHDs are to be used as mitigating devices in the southern hemisphere. A review of salmon aquaculture in British Columbia, Canada, noted that AHDs appear to lose effectiveness over time as pinnipeds become accustomed to them or deafened by them, or are strongly motivated by hunger or by their previous successes. The report recommended that their use be phased out.

Seal crackers are another type of acoustic device that has been used by some finfish farms. These are fire crackers which explode underwater and they are commercially available from the USA. They have been used in Tasmania since 1986 in an attempt to deter marine mammals from interacting with aquaculture and wild fisheries (Pemberton 1989). In the dropline fishery targeting trevalla (Family *Centrolophidae*), crackers were not successful in deterring killer whales from damaging hooked fish. Reports of the efficacy of seal crackers in deterring seals from interacting with commercial gill net fishing operations and finfish aquaculture have been mixed. Most users reported that while they may be effective initially, with repeated use seals become rapidly accustomed to them. If used judiciously, seal crackers may be effective for deterring sub-adult seals from interacting with gill nets (M. Cuthbertson, personal communication to D. P. 2000).

Experience elsewhere is consistent with the Tasmanian situation—seal crackers are effective in the short-term but with continued use, pinnipeds learn to ignore or avoid the noise and effectiveness rapidly decreases (Gearin 1986; Fraker *et al*. 1998). Seal crackers also pose a risk to seals and operators. Appropriate use is difficult to ensure, with considerations of animal welfare, Occupational Health and Safety and regulation issues being central to their application.

Minimising entanglements

Entanglement of cetaceans and pinnipeds in finfish farms has been the subject of few studies world wide (Pemberton 1996; Kemper and Gibbs 1997, 2001). Many of the recommendations that apply for reducing predator damage also hold for minimising marine mammal entanglements. For example, 1) adequate net tension reduces billowing, 2) enclosing the anti-predator net at the bottom stops dolphins and pinnipeds from being trapped between the cage and anti-predator nets, 3) eliminating food wastage discourages other prey species and, therefore, dolphins and pinnipeds from foraging around the nets and 4) reducing the mesh size of the nets to less than 10 cm and repairing holes reduces substantially the chance of marine mammal entanglement. In addition, pens that are not in use, and therefore often poorly maintained, are an entanglement threat. The simple remedy is to have all non functioning nets removed from the water.

Minimising ecological impacts

Mitigating against the effects of mariculture is problematic because little is known about the ecology of the marine mammal species inhabiting the southern hemisphere, particularly the inshore dolphins that overlap with aquaculture. For example, when planning a new aquaculture venture, it is difficult to know what foraging and calving habitats are important for inshore dolphins so that these can be avoided. In addition, threatened species, such as the dugong, may be adversely affected by disturbance or habitat loss in coastal areas due to shellfish farming. The effects of aquaculture on local habitats could have long-term impacts (e.g. loss of seagrass beds). Perhaps more importantly, local and wider-ranging population sizes are almost never known so the effect of entanglement mortality on the long-term viability of inshore populations is impossible to predict. All interactions will vary in the detail and dynamics so solutions need to be tailored to each specific case.

FUTURE RESEARCH

Apart from some specific areas of research suggested in the previous sections, there is a need for studies to look at the 'big picture' and involve long-term research on the ecology of species affected or potentially affected by aquaculture. To date, much of the research effort has been focussed on those interactions detrimental to the finfish industry, usually with the aim of finding the 'cure' not the 'nature' of the problem. Investigations are needed as to how and why the interactions occur, followed by testing different solutions in a scientific manner.

An important area that does not seem to have been studied is the interaction of different types of aquaculture in the same area and the combined effects of these on marine mammals. In some cases, such as the 10th Region, Chile, this concentration is extreme and the number of marine mammals is high.

All research on marine mammal interactions would benefit from more rigorous and transparent monitoring but this is very hard to achieve because operators fear reprisal and public/market reactions to events that are negative to marine mammals (DeMaster *et al*. 1985). Monitoring should be conducted by independent researchers, even if the funds supporting such programs come from the aquaculture industry. In addition, commercial operators are reluctant to continue practices that appear to them to be ineffective, even if that cannot be demonstrated sufficiently rigorously to convince the investigator.

IS MARINE AQUACULTURE ECOLOGICALLY SUSTAINABLE?

One of the difficult questions facing southern hemisphere nations is whether or not finfish and shellfish aquaculture at their present and future levels of development will result in adverse effects on the marine ecosystem. Black (2001b) believes that intensive aquaculture, especially those forms dependent on fishmeal and fish oil to feed carnivorous finfish species, is the most challenged in terms of its sustainability on a broad scale. That is not to say that shellfish, seaweed and herbivorous fish aquaculture do not pose problems but that their effects are likely to be more local in nature rather than affecting the whole marine ecosystem. Naylor *et al*. (2000) provide the most convincing evidence that it does not make economic and ecological sense to harvest fish (or krill) from the sea to feed caged carnivorous fish because more is required to feed them than herbivorous species (2–5 kg compared with 1.9 kg). Naylor and her colleagues believe that the growing aquaculture industry must reduce wild fish inputs and adopt more ecologically sound management procedures. In Australia, at least two species of fish, pilchards (*Sardinops neopilchardus*) and jack mackerel (*Trachurus declivis*), are being harvested for finfish food and both are keystone prey species in the food chain of marine vertebrates, including marine mammals such as Australian fur seals (Gales and Pemberton 1990, 1994; Gales *et al*. 1993; Brothers *et al*. 1993; Hedd and Gales 2000) and short-beaked common and bottlenose dolphins (Kemper and Gibbs 2001).

In addition to the pressure on wild fish stocks from direct harvesting, marine finfish culture has had detrimental environmental impacts through nutrient and organic enrichment, benthic changes, and parasite and disease transfer to wild populations (see review by Pearson and Black 2001). Two mass mortalities of pilchards along the southern coast of Australia during the mid 1990s may have been caused by a herpes virus that possibly came from imported pilchards used as food in the tuna feedlots at Port Lincoln (Gaughan *et al*. 2000). Harmful algal blooms have also been implicated in the death of many tonnes of caged tuna during 1996 (Hallegraeff 1997) and eutrophication of coastal waters is considered a major problem for many of Australia's estuaries and enclosed coastal waters (Zann 1995). Cheshire *et al*. (1996) investigated the environmental effects of tuna feedlotting at Port Lincoln. They found that the epibenthic communities were impacted up to 150 m from the cages and that there were significant infaunal communities within 20 m: both changes resulted from a large build up of organic detritus. Many of the feedlots have since moved to more open water, where the effects on the immediate benthos would be less detrimental as a result of currents. Pearson and Black (2001) reviewed the environmental impacts of finfish aquaculture and concluded that the rapid growth rate of the industry had outstripped the understanding of the environmental consequences and that this had led to many problems. Examples of rapid industry expansion in the southern hemisphere are cited above (see Mariculture in the southern hemisphere).

Some types of aquaculture have had substantial effects on habitats that are important for biodiversity and the marine food chain and these, in turn, affect marine mammals. The most obvious example of this is the clearing of tropical mangrove forests for shrimp farming and the polluting of mangroves by effluents from land-based shrimp ponds, particularly in Ecuador and Indonesia (Kaiser 2001; Black 2001b). Mangroves are nursery areas for many species of fish and destroying them would certainly affect some fish stocks. Local marine mammals, such as dugongs and inshore dolphins, as well as offshore species are likely to be adversely affected.

CONCLUSIONS

Marine mammal interactions with aquaculture, particularly finfish farms, are inevitable. To minimise these, we believe that stringent requirements, including environmental impact assessments that predict the effects of habitat loss, nutrient concentration, monoculture and entanglement risk, should be put in place *before* permit applications are approved to develop new aquaculture initiatives or to expand existing operations. These requirements should include identifying and planning for predator interactions and should be contingent upon gaining financial backing, environmental audit and fisheries management approvals. Formally-recognised stakeholder groups should be involved in the permitting process, and 'Solutions Groups' should be set up on a regional scale. Co-operation and openness between industry, government, the community and conservation groups should result in aquaculture that is more ecologically sustainable and therefore better for marine mammals and for aquaculture ventures.

ACKNOWLEDGMENTS

The authors would like to thank all those who provided information to this review and who suggested people to contact to make it more complete. David O'Sullivan and Meg Ryan generously assisted with background data on aquaculture statistics in Australia and worldwide. Tony Flaherty is thanked for his support of the study of South Australian interactions, his knowledge of aquaculture that he generously shared with C. K. and for comments on the manuscript. The study of carcasses entangled in Port Lincoln tuna farms was, in part, supported by funding from Environment Australia to C. K. We thank the many finfish farmers in Tasmania, especially Peter Warner (Tassel Pty Ltd), who were very co-operative with studies of interactions. Mike Greenwood and Fiona Hume are thanked for their parts in interaction studies of marine mammals in Tasmania. M. Sepulveda kindly provided access to her unpublished MSc thesis. Manuel Martinez-Espinosa (FAO Italy) is thanked for providing access to vital information on aquaculture statistics for Latin America.

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