Review of the Ecological Effects of Marine Finfish Aquaculture: Final Report

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Review of the Ecological Effects of Marine Finfish Aquaculture: Final Report

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Prepared for

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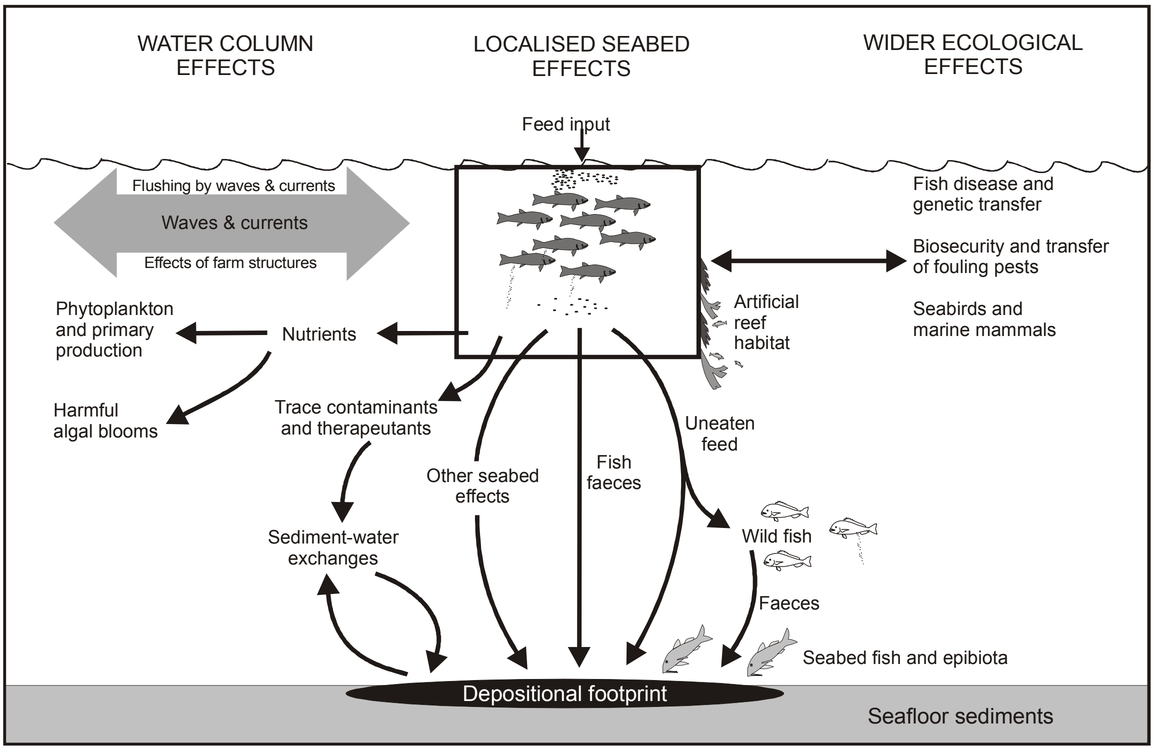
EXECUTIVE SUMMARY

OVERVIEW

The marine finfish aquaculture industry in New Zealand is small by comparison with many other countries, and based primarily around sea-cage farming of King salmon (*Oncorhynchus tshawytscha*) at sites in the Marlborough Sounds, Akaroa Harbour, and Big Glory Bay (Stewart Island). There has been recent interest in expansion of the finfish industry to new areas and new species such as yellowtail kingfish and groper, among others. A trial kingfish farm is already established in the Marlborough Sounds. This report reviews existing information on the ecological effects of finfish farming, providing background knowledge that will assist with resource management decisions in relation to future development. However, this review is not intended to be an assessment of environmental effects that could be used directly in relation to a resource consent application; any assessment for such purposes would need to consider a range of site-specific issues.

The ecological effects of finfish farms have been intensively studied world-wide, primarily in relation to the development of the salmon farming industry. Finfish held in aquaculture are fed artificial diets in the form of food pellets, and early work highlighted significant effects on the seabed beneath farm structures, which arose from the deposition of waste (i.e., uneaten) feed and faecal material from the farmed stock. There is now a considerable amount of scientific literature on the seabed effects of salmon farms from both New Zealand and overseas. More recently a range of other potential effects and interactions have also been recognised, most of which are represented in the following diagram. Below we provide a summary of our findings for each of these issues, along with management and mitigation approaches.



ECOLOGICAL EFFECTS OF FINFISH FARMS AND OPTIONS FOR MITIGATION

Seabed and water column effects: The deposition of uneaten feed and faeces can have pronounced effects directly beneath finfish cages, but there is a rapid improvement in environmental conditions with increasing distance from farm structures (over tens or hundreds of metres). Seabed effects are largely reversible, although recovery is likely to take many months or years, depending on water flushing characteristics. Nutrient enrichment in the water column occurs in the vicinity of finfish farms. Although nutrient enrichment has the potential to stimulate algal blooms, studies in New Zealand and overseas have not linked blooms to fish farming activities; presently, finfish farming in New Zealand is of a low intensity and appears to be well within the carrying capacity of the environment. Seabed and water column effects can be reduced by locating farms in well-flushed areas, in areas where species and habitats of special value are not present, or where flushing characteristics alter deposition patterns to a point where adverse effects do not occur. A range of other steps to mitigate effects have already been implemented at salmon farms in New Zealand. For example, feed wastage is minimised and stocking densities managed at levels that ensure the environment is maintained in a condition that is considered, by stakeholder consensus, to be acceptable.

Habitat creation and biosecurity: Finfish farms and other artificial structures in marine environments provide a three-dimensional suspended reef habitat for colonisation by fouling communities. The aggregation of wild fish around artificial structures is well recognised, and fish in the vicinity of fish farms may feed on waste feed, thereby attracting larger fish. Several studies have highlighted the possible role played by fouled structures within the ecosystem, such as enhancement of local biodiversity and productivity. The role of aquaculture structures as reservoirs for the establishment of pest organisms (e.g., fouling pests) is also recognised. The development of finfish farming in New Zealand therefore has the potential to exacerbate the domestic spread of pest organisms, although various management approaches can be implemented to reduce such risks. Some of these approaches (e.g., codes of practice, treatments for infected structures) have already been implemented by aquaculture companies in New Zealand in response to existing pests.

Seabirds and marine mammals: Potential effects on seabirds and marine mammals (seals, dolphins and whales) relate mainly to habitat modification, entanglement in structures and habitat exclusion. For seabirds a range of potential effects are recognised, but none are well understood. New Zealand fur seals are a problematic species around salmon farms, leading to use of predator exclusion nets around most sea-cages. In approximately 25 years of sea-cage salmon farming in New Zealand there have been four entanglements of marine mammals (2 seals, 2 dolphins) in predator nets. Subsequent management responses (e.g., changes to net design, development of protocols for net changing) mean that entanglement is unlikely to be a significant ongoing issue. Exclusion of marine mammals from critical habitat by finfish farms is highly unlikely at present in New Zealand given the small scale of the industry, and risks from future development could be minimised by appropriate site selection.

Genetics, disease transfer and effects of escaped fish: Potential interactions between farmed and wild fish populations include: competition for resources with wild fish and related ecosystem effects from escapee fish, alteration of the genetic structure of wild fish populations by escapee fish, and transmission of pathogens from farmed stocks to wild fish populations. These risks have been highlighted in overseas studies (primarily in relation to salmon farming), but appear to be relatively minor issues for New Zealand at present. For example, effects from escapee salmon are likely to be minimal given the small scale of the industry, and the limited salmon numbers in wild populations within existing grow-out regions. For species such as kingfish, and other candidate species that may be trialled in New Zealand, significant ecosystem effects from escapees are unlikely. For kingfish, significant genetic influences on wild stocks are unlikely, but for other species would need to be considered on a case-by-case basis. Disease is not a significant issue within the New Zealand salmon industry, however issues could arise with kingfish or other new species. This situation could lead to the use of therapeutants (i.e., pharmaceutical medicines) to manage disease risks.

Therapeutants and trace contaminants: Most therapeutants have limited environmental significance as they are usually water soluble and break down readily. However, some are administered as feed additives, hence they can be deposited on the seabed. Increased levels of trace metals (zinc and copper) can be found in sediments beneath fish cages in New Zealand and overseas. Zinc is a nutritional supplement necessary for maintaining fish health, and copper comes from antifouling paint whose use is necessary to minimise the build-up of fouling organisms. Both zinc and copper are likely to bind with sediments and organic material, which will naturally mitigate their risk to the environment. Other chemical contaminants such as dioxins, polychlorinated biphenyls (PCBs) and heavy metals like mercury, are globally ubiquitous compounds that accumulate in animal tissue (including humans) via the food chain. In New Zealand PCB and dioxin levels in sea-cage salmon are well within health guidelines stipulated by various regulatory agencies, and are unlikely to be a risk to the wider ecosystem. The New Zealand salmon industry and feed supply companies implement various measures to minimise contaminant inputs to the environment, which will likely lead to reduced contaminant loads in the future. With the further development of the finfish farming industry, it is important that similar mitigation measures are encouraged as part of ‘best management practice’.

SYNTHESIS AND CONCLUSIONS

Although there will always be a site-specific element to the magnitude and significance of finfish farm impacts, most of the main effects are reasonably well understood, reflecting the considerable research and monitoring that has been conducted in New Zealand and overseas in relation to the salmon industry. Collectively, this work indicates that the effects of salmon and other finfish farms are often highly localised and largely reversible, and can be managed in various ways to meet acceptable standards. Hence, at the present low level of finfish production in New Zealand the wider ecological significance of many of the issues we describe in this report is likely to be minor. Nonetheless, there are some exceptions to these general statements. Using criteria to gauge the relative ecological significance of the various issues identified, we highlight that biosecurity risks relating to the spread of pest organisms are an important consideration. Although the magnitude of pest-related effects may be less than in the case of seabed impacts, by comparison with all other ecological stressors the spread of pest organisms by finfish farming activities can occur at regional scales, and potentially lead to irreversible changes to coastal ecosystems. The magnitude of seabed impacts is also relatively high, but seabed effects are highly localised and largely reversible in the medium to long term. Furthermore, while the ecological significance of seabed impacts may be high in a relative sense, in absolute terms the broader consequences can be mitigated by appropriate site selection. For issues other than those relating to pest organisms and seabed effects, ecological significance is arguably less, at least at the present level of finfish (primarily salmon) aquaculture in New Zealand. In some instances this reflects low likelihood events that are presently well-managed, such as adverse effects on marine mammals. Similarly, in the case of disease transfer and genetic alteration of wild stock, the ecological effects of present developments are either minor or can be effectively managed.

Changes in ecological risk associated with fish farming, and in the relative importance of the different ecological issues, are likely to result from future developments that involve the aquaculture of new species or a significant increase in the number or size of finfish farms. In relation to new species, interactions between farmed and wild fish stocks, and the associated potential for genetic alteration and disease should be carefully considered, as should the use of chemical therapeutants to manage disease risk. For the other issues discussed in the report, ecological consequences are likely to be similar for most of the candidate species that may be farmed in the future, with effects related primarily to the local intensity and geographic scale of farming (assuming procedures for appropriate site selection and effective management are in place to mitigate any adverse effects). Note, however, that for large-scale new developments, cumulative and threshold effects will also need to be considered. For example, high intensity finfish farming within individual embayments could lead to nutrient enrichment at levels of greater significance (in relation to algal bloom formation) than presently appears to be the case.

Where new developments are proposed it is almost inevitable that some areas of uncertainty will arise for which answers regarding ecological risk are not straightforward. At the farm scale, mitigation of poorly understood risks may rely on industry 'best management practice' or adherence to internationally accepted guidelines, at a level of effort that is reasonable within the context of sources of risk from other activities. The New Zealand salmon farming industry already has codes of practice for many aspects of its operations. In relation to future finfish farming activities, consideration should be given to development of a more comprehensive environmental code of practice for the industry as a whole. At greater scales of development (i.e., where multiple farms or atypically large farms are proposed) it may be appropriate for development to proceed in a staged manner within an adaptive management and monitoring framework. Staged development will be of particular importance for issues where potential cumulative effects are recognised.

Finally, we note that judgements as to the ecological significance of finfish farming should ideally be made in relation to other sources of environmental risk to coastal systems, so that the effects of finfish aquaculture are placed in context. A risk-based framework (the 'Relative Risk Model') for this purpose was recently applied in relation to mussel farm development in the Firth of Thames. In that approach, the relative risks to predefined endpoints (particular species and populations, and habitats) from a number of sources and stressors (agricultural land use, climate change, marine farming, fishing, urban development, etc.) were investigated. The outcome of the Firth of Thames work was that relative risks were identified for all of the habitats in question from all of the stressors. Such methods can be applied in a defined area (e.g., a harbour) or across multiple regions, and provide a defensible basis for making resource management decisions.

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1. INTRODUCTION

1.1. Background

Sea-cage farming of finfish is a well established industry in many countries world-wide, and is currently undergoing expansion because of a strong and growing demand for fish products at a time when wild stocks have been over-exploited. Recent developments include diversification from traditional species like salmonids to include true marine species, and a move from farming in sheltered waters to relatively wave-exposed areas, which has been facilitated by technological developments in cage design and construction. The emerging status of the finfish industry in New Zealand is a reflection of this global trend. To date the marine finfish industry in New Zealand has been based around sea-cage farming of King salmon (*Oncorhynchus tshawytscha*), and is relatively small.

There are five main salmon farms in operation in New Zealand; four in the Marlborough Sounds (e.g., Figure 1) owned by The New Zealand King Salmon Company Ltd, and one in Big Glory Bay on Stewart Island owned by Sanford Ltd. Two smaller sites are operated in Akaroa Harbour on Banks Peninsula. The New Zealand distribution of these sites is shown in Figure 2 and a history of the industry's development summarised in Appendix 1. The salmon industry generates a market revenue of approximately $88 million per year compared with $237 million from the combined Greenshell™ mussel and Pacific oyster sectors. However, there has been recent interest in new salmon farm sites and a number of new finfish species, including yellowtail kingfish (*Seriola lalandi lalandi*), for which a trial farm is in operation in the Marlborough Sounds. *Seriola lalandi* (and sub species) are already being cultured in South Australia and on a large scale in Japan (Poortenaar et al. 2003). Other potential culture species include groper, bluenose, blue warehou, butterfish, flatfish, trevally, tunas, snapper and seahorses (Lee and Smith 2005).

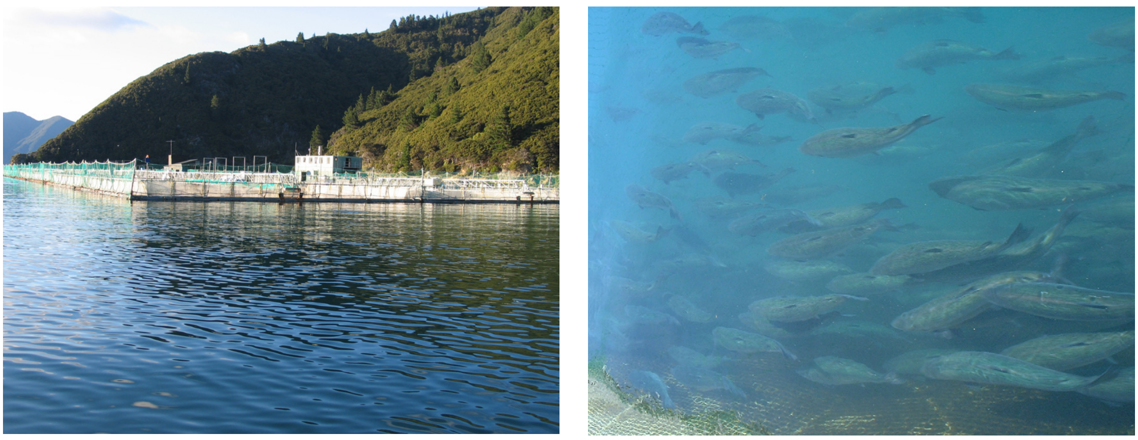


Figure 1 Typical sea-cage salmon farm in the Marlborough Sounds.

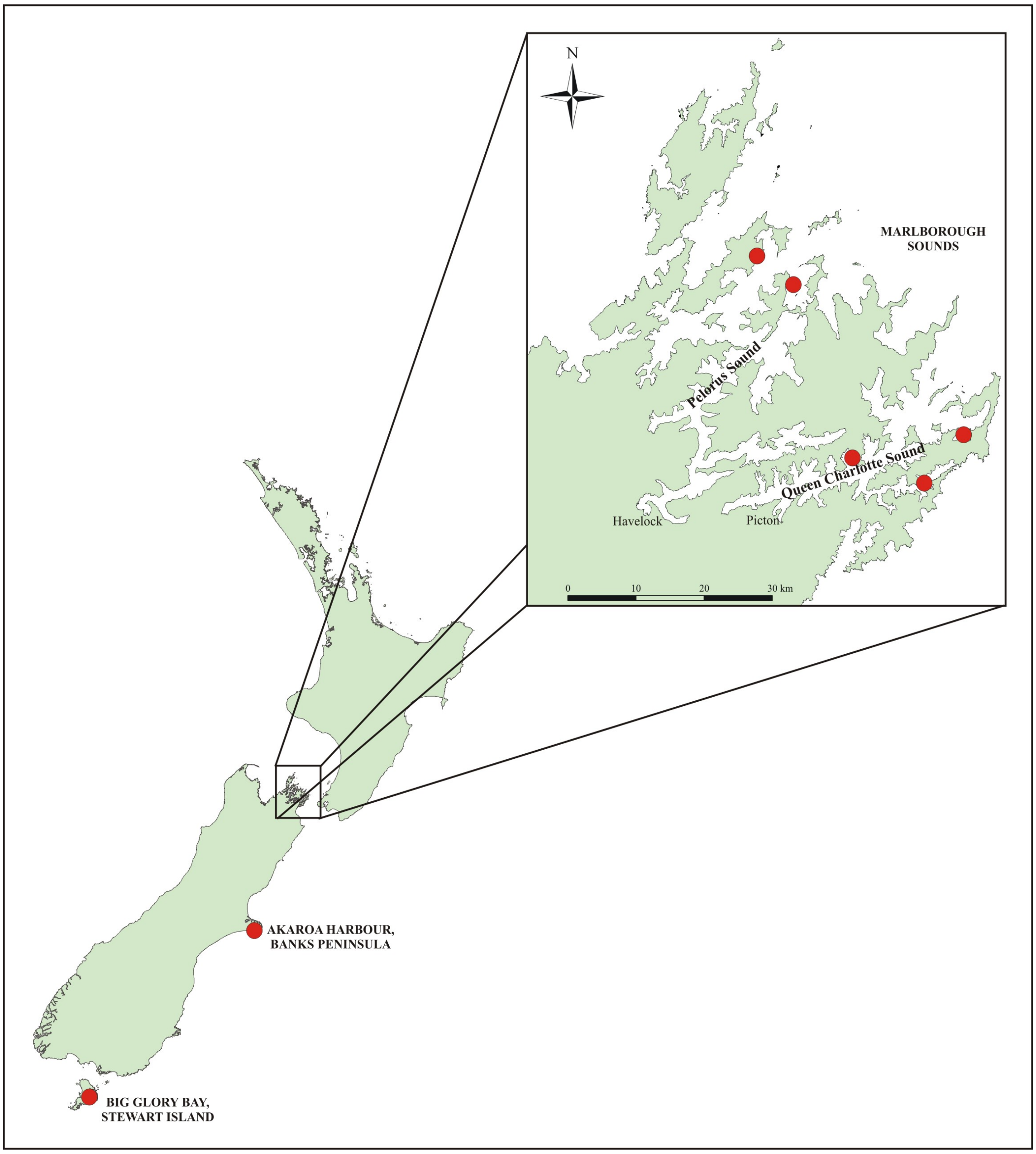


Figure 2 Location of sea-cage salmon farms in New Zealand.

Informed resource management decisions for future finfish farm development in New Zealand will require knowledge of the actual or potential environmental issues associated with the industry, identification of the most significant risks, and key areas of uncertainty regarding environmental effects. As part of this, regional councils and the marine farming industry have recognised the need to understand the state of knowledge regarding the present effects of the finfish industry in New Zealand, and the extent to which overseas experience is relevant. Currently, this type of information is not readily available to the public, nor is it in a form that is easily assimilated by non-scientists. It is typically collected by the industry for resource consent or marine farming permit requirements, or generated through government-funded research programmes. Furthermore, most of the existing information relates to salmon farming and has a situation-specific focus. In the Marlborough Sounds alone, for example, more than fifty environmental monitoring or site assessment reports have been produced in relation to sea-cage salmon farming over the last two decades. Hence, the Ministry of Fisheries (MFish) has contracted the Cawthron to conduct a review of existing information on the ecological effects of finfish farming, in order to provide a comprehensive synthesis of existing knowledge.

1.2. Scope and purpose of this report

This review is intended to provide a foundation of knowledge that will assist with resource management decisions in relation to future development of the finfish farming industry. It is important to recognise, however, that the report presents information that is of a general nature only. It is not intended to be an assessment of environmental effects that could be used directly in relation to a resource consent application; any assessment for such purposes would need to consider a range of site-specific effects. Furthermore, the report focuses on ecological effects only, whereas a broader range of effects and benefits on the coastal environment and communities will be relevant to resource management decisions. Finally, it should be recognised that we limit the scope of the report to a discussion of coastal issues relating to finfish farm structures and operations (i.e., the grow-out or sea rearing stage of finfish farming) and do not consider wider 'off-site' effects such as those from land-based hatchery rearing and product processing.

Our review is based on information from a variety of sources including international and national journals, and 'grey' literature, which in this case primarily relates to environmental monitoring reports written for the New Zealand sea-cage salmon farm industry (New Zealand King Salmon and Sanford Ltd). We also include personal communications with stakeholders where appropriate. Our report is largely structured according to the topics that were provided by MFish in the project brief (tender document IPA-5006-08), with the scope expanded to include additional aspects identified during our review. Sections 2 - 4 provide an overview of the various issues, along with environmental management and mitigation approaches that are commonly used or might be applicable to future finfish farming in New Zealand. Section 5 provides a summary and synthesis of the review information, and evaluates the relative ecological significance of the various issues identified.

2. OVERVIEW OF ECOLOGICAL EFFECTS

The ecological effects of finfish farms have been intensively studied world-wide, primarily in relation to the development of the salmon farming industry. Early in the development of that industry, concerns were focused on farm wastes and their effect on the seabed and, to a lesser extent, the water column (e.g., Brown et al. 1987; Gowen and Bradbury 1987; Edwards 1988). Finfish held in sea-cages are fed artificial diets in the form of food pellets, and early studies highlighted significant effects on the seabed beneath and adjacent to farm structures, which arose from the deposition of waste (i.e., uneaten) feed and faecal material from the farmed stock. These problems were partially alleviated with the introduction of high quality feeds and by minimising losses. Nonetheless, seabed issues are still highly relevant, and have remained the focus of most of the scientific literature that has emerged on the ecological effects of salmon and other finfish farms. More recently, the issue has expanded to recognise wider sources of seabed impact, such as the accumulation of trace contaminants derived from nutritional products or from the use of antifouling coatings on farm structures.

As seabed effects have become increasingly well documented and understood, attention is slowly shifting to many of the broader but sometimes less tractable ecological issues that arise with the development of finfish farming. We have attempted to capture many of these schematically in Figure 3, with additional issues also discussed in subsequent sections. The range of potential effects we consider includes: the potential for finfish farm nutrients to stimulate the development of algal blooms, the use and effect of therapeutants, the accumulation of contaminants in the food chain, effects on seabirds and marine mammals, and interactions of caged fish with wild fish (including the potential for disease and parasite outbreaks, and genetic influences from escapee fish).

In our report we also recognise the role of fish farm structures as artificial reefs, and related to this the biosecurity risk from industry operations, in particular the transfer of unwanted biofouling pests. As part of our assessment, we describe the role of water currents and waves in mitigating a number of ecological effects, because these environmental characteristics affect the flushing and dispersal of farm wastes. In this respect, an important effect of the farm structures is to reduce natural flushing characteristics thereby altering the nature and magnitude of fish farm effects. It is important to recognise that most of the available literature, and hence our review, focuses on the effects of small finfish farms individually. However, the sustainability of multiple or large-scale finfish farm developments is also a key consideration that we discuss in this report.

The technical review in the report consists of two main sections: Section 3 addresses seabed and water column effects, as these are inter-related to some extent, and Section 4 addresses wider issues. Within each section we provide a review and synthesis of the pertinent literature, and discuss present and potential management and mitigation strategies. The length of each section and sub-section in part reflects where the depth of knowledge is greatest rather than the actual or potential significance of each issue. Similarly the order in which we present the information is not meant to imply importance, it merely reflects the way we have chosen to structure the subject material to help the readability of the report, especially given that many of the sub-sections are inter-related. In order for the reader to discriminate between the New Zealand situation compared with overseas experience, we use paragraph divisions throughout each sub-section as appropriate. For some issues, however, New Zealand and overseas experience is similar, and the available knowledge is collectively discussed in the text to avoid repetition. Where this collective approach has been taken it is stated as such at the beginning of each relevant section.

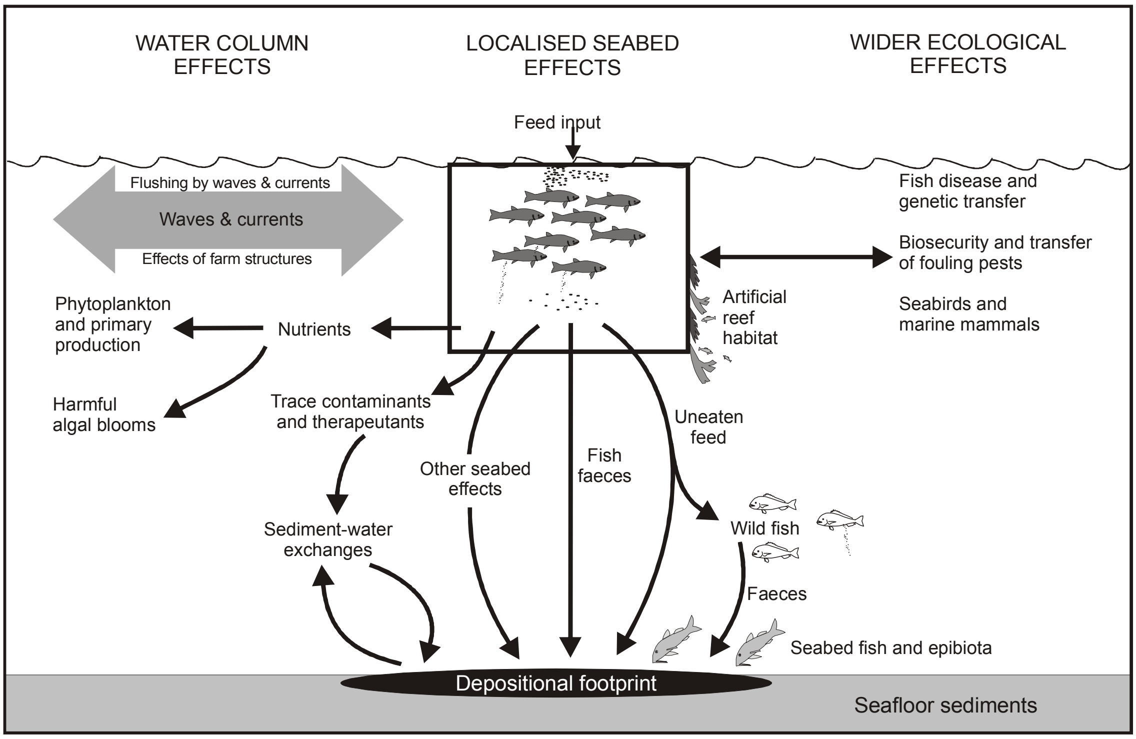


Figure 3 Overview of actual and potential ecological effects from marine finfish farms.

3. SEABED AND WATER COLUMN EFFECTS

3.1. Seabed effects

3.1.1 Background

Fish farms are almost invariably sited above soft-sediment habitats (as opposed to rocky habitats), hence information on seabed effects relates primarily to physico-chemical and ecological changes in such areas. Most of the literature describes the effects of salmon farming, but studies for other finfish species (e.g., yellowtail kingfish, European sea bass, red sea bream) reveal that seabed impacts are similar (e.g., Karakassis et al. 1999; Rajendran et al. 1999; Mazzola et al. 2000; Yokoyama 2003). The dominant effect on the seabed arises from the deposition of faeces and uneaten feed, which leads to over-enrichment of the seabed due to the high organic content of the deposited particles. Microbial decay of this waste material can dramatically alter the chemistry and ecology of the seafloor (e.g., Forrest 1996a, 2001; Gowen and Bradbury 1987; Wildish et al. 2001; Brooks et al. 2003; Carroll et al. 2003; Chou et al. 2004; Hopkins et al. 2004a; Sara et al. 2004; Chagué-Goff and Brown 2003, 2004, 2005; Lampadariou et al. 2005). More than 20 years of research and investigation both within New Zealand and overseas has consistently shown that finfish farm discharges can change well-aerated and species-rich soft sediments in the vicinity of farm cages into anoxic (oxygen-depleted) zones that can be azoic (devoid of life) in extreme cases, or dominated by only a few tolerant sediment-dwelling species. These types of effects, and the factors that affect their severity, are discussed below in relation to feed and faecal deposition. We present New Zealand and overseas experience together, as the general types of effects are the same. In Section 3.1.4 we widen the discussion to consider other factors that may contribute to seabed effects in certain circumstances, and in Section 3.1.5 consider the timescales and processes of recovery from adverse impacts.

3.1.2 Nature and magnitude of depositional effects

The depositional 'footprint' of a typical finfish farm (as depicted in Figure 3) extends tens to hundreds of meters from the point of discharge (Brown et al. 1987; Karakassis et al. 2000; Schendel et al. 2004; Chagué-Goff and Brown 2005), often in an elliptical pattern that is skewed in the direction of prevailing currents (e.g., Hopkins et al. 2004a). Effects tend to be most evident directly beneath the farm stock, and exhibit a strong gradient of decreasing impact with increasing distance, which is consistent with other organic enrichment gradients (see review by Pearson and Rosenberg 1978). Farm-derived particulates may disperse further than the footprint of measurable effects, as shown by a recent overseas study detecting farm wastes up to 1 km from the source (Sara et al. 2004). Such findings highlight that the seabed environment beyond the effects footprint may be exposed to farm-derived materials, but has a capacity to assimilate them without exhibiting any measurable ecological changes.

Excessive levels of organic enrichment directly beneath finfish farms are typically manifested via a suite of different 'indicators'. Anoxic conditions within the sediment are evident as a strong 'rotten egg' smell of hydrogen sulphide and a black colour throughout the sediment profile (Figure 4). Such conditions will typically be accompanied by visible white/cream coloured patches across the seafloor, which indicates the presence of mat-forming filamentous bacteria such as *Beggiatoa* sp. (Figure 5). Under extreme conditions, sediment out-gassing also occurs, which will be evident as gas bubbles emerging from the sediment surface (Gowen and Bradbury 1987; Iwama 1991; Hopkins et al. 2004).

Figure 4 Mud samples from beneath salmon cages in the Marlborough Sounds. Left: black anoxic sediments from beneath cages compared with brown sediments from a control site beyond the influence of the farm. Right: sediment grab sample with black sediment and faecal material (orange) evident.

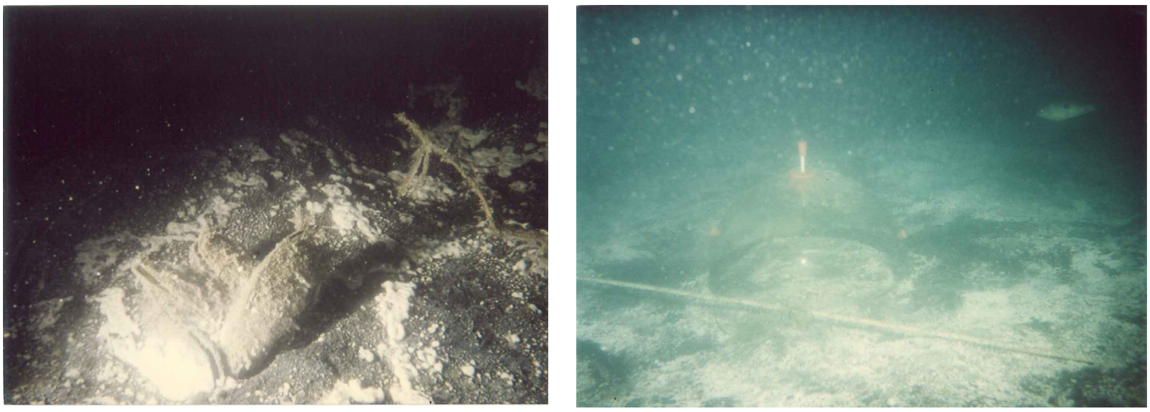


Figure 5 Seafloor beneath salmon cages in the Marlborough Sounds showing bacterial cover (*Beggiatoa* sp.) present as a result of pronounced organic enrichment.

The hydrogen sulphide component of the out-gassing can adversely affect the health of fish and other fauna (Gowen and Bradbury 1987; Black et al. 1996). Under such conditions, levels of sediment organic matter and nutrients (e.g., organic carbon, nitrogen and phosphorus) will also usually be significantly elevated by comparison with background sediments (Karakassis et al. 2000; Gao et al. 2005). Note that the sediment can also be enriched with trace contaminants (e.g., zinc, copper) sourced from feed or antifouling agents (Schendel et al. 2004). These trace contaminants can be toxic at high concentrations, although in organic-rich sediments beneath fish farms may not be in a 'bioavailable' form where toxic effects could be exerted (see Section 4.8).

Enrichment to the extent that results in a seabed devoid of sediment-dwelling 'infauna' (animals that inhabit the sediment matrix) has been described in the past for most salmon farms in New Zealand (e.g., Edwards 1988; Roper et al. 1988; Forrest 1996a; Chagué-Goff and Brown 2003, 2004, 2005; Hopkins et al. 2006a, b, c), but the development of management strategies to reduce this risk has largely been successful (Section 3.3.4). With distance from the farm, a rapid reduction in the severity of physico-chemical effects leads to an associated reduction in ecological effects. Most studies characterise ecological changes using infaunal communities (and other complementary techniques); the presence or absence, abundance and diversity of such organisms are well-recognised indicators of seabed health or enrichment status (Pearson and Rosenberg 1978; Brown et al. 1987).

Typical changes in infauna along an enrichment gradient from a finfish farm are shown in Figure 6. Along this gradient, an area of enhanced seabed productivity can occur just beyond the zone of greatest effects, which is evident as the proliferation of one or a few enrichment-tolerant 'opportunistic' species such as the marine polychaete worm *Capitella capitata* (e.g., Roper et al. 1988; Mazzola et al. 1999; Karakassis et al. 2000; Mazzola et al. 2000; Hopkins and Forrest 2002; Hopkins 2003; Chou et al. 2004; Hall-Spencer et al. 2006). Typically, species richness declines with increasing enrichment, although an area of increased richness can sometimes be evident just beyond the impact zone.

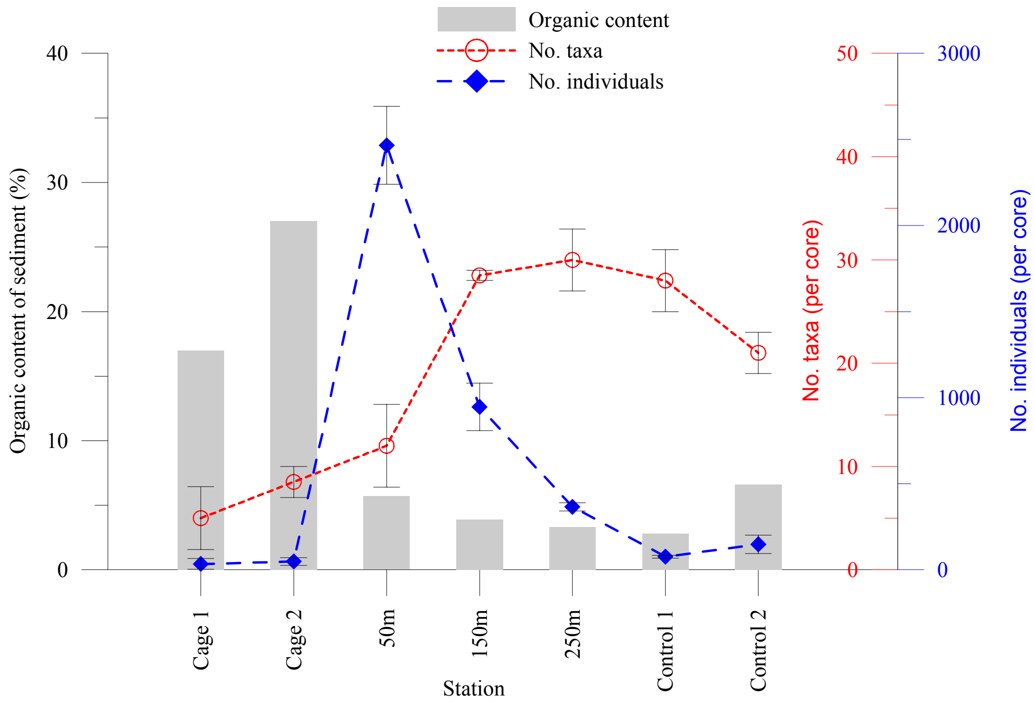
3.1.3 Factors affecting the magnitude and spatial extent of seabed effects

The magnitude and spatial extent of seabed effects from finfish farms are a function of a number of inter-related factors, which can be broadly considered as farming attributes and environmental attributes, as follows:

1. Farming and waste generation: These include attributes that affect the mass load of organic material deposited to the seabed, namely:

- Fish stocking density, and settling velocities of fish faeces. The latter appears to vary considerably among fish species (ca. 0.4 – 6.0 cm/s; Magill et al. 2006), hence may be a factor that influences deposition levels.
- The type of feed and feeding systems, the feeding efficiency of the fish stock, and the settling velocities of waste feed pellets. Depositional rates can also be influenced by farm waste consumption from wild fish assemblages as described in Section 4.3. Clearly, it is in the interests of the fish farmer to minimise feed wastage. As well as economic costs associated with waste feed, excessive food loss can organically enrich the seabed to a point where water column effects occur (e.g., hydrogen sulphide production) and fish health is compromised (see Sections 3.2 and 4.10.3).

(A) Marlborough Sounds salmon farm enrichment gradient



(B) Schematic infaunal change as a result of enrichment

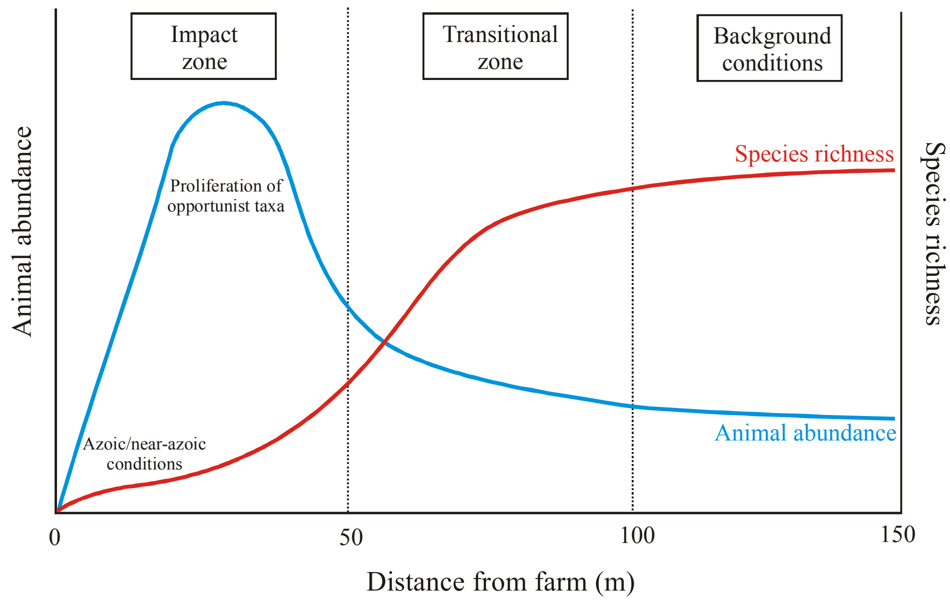


Figure 6 Changes in sediment organic content or infaunal communities along typical salmon farm enrichment gradients. (A) data from a salmon farm in the Marlborough Sounds; (B) stylised depiction of changes in infaunal abundance and species richness (number of taxa).

- The type of cage structure may also influence depositional effects through differences in fish holding capacity, which affects feed loadings and may affect feeding efficiencies. Furthermore, cage design and position may affect depositional patterns through altering the way water currents move around a farm site. Any reductions in flow will reduce waste dispersal and flushing (see Section 4.9) potentially resulting in effects that are relatively localised but also more pronounced. Such effects can be minimised through appropriate cage design and orientation to ensure minimal obstruction of water currents.

2. **Environmental characteristics:** The capacity of the environment to disperse and assimilate farm wastes is mainly related to water depth and current speeds, although assimilative capacity may also vary seasonally in relation to factors such as water temperature. Nonetheless, because water depth and current speeds affect the extent of flushing, they are the primary attributes that modify both the magnitude and spatial extent of seabed effects. Increased flushing not only reduces localised sedimentation and accumulation of organic matter, but it also increases oxygen delivery to the sediments, thus allowing for more efficient mineralisation of farm wastes (Findlay and Watling 1997). For example, deep sites (> 30 m) located in areas of strong water currents will have depositional footprints that are less intense and more widely dispersed than shallow, poorly flushed sites (e.g., Molina Dominguez et al. 2001; Pearson and Black 2001; Aguado-Gimenez and Garcia-Garcia 2004).

Such contrasts are clearly evident in the case of salmon farming in the Marlborough Sounds. Several existing farms in areas of weak flushing such as Forsyth Bay and Ruakaka Bay have localised but quite pronounced effects (e.g., Forrest 1996a; Govier and Bennett 2007a, b). In fact, farming has failed in a number of areas in the Marlborough Sounds and Stewart Island where flushing has been inadequate or water temperatures too warm (Appendix 1). By contrast, at an existing farm in the high current environment of Tory Channel in Queen Charlotte Sound, the intensity of effects is substantially less (Forrest 1996b; Hopkins 2004). In this example, Forrest (1996b) describes a variety of surface-dwelling animals and red algae on the seabed beneath the salmon farm, despite enrichment evident within the sediment profile and infaunal communities.

Note that the significance of ecological effects is also a function of site-specific values, such as the presence of species or habitats that are sensitive to depositional effects or are of special interest (e.g., high conservation value, keystone species). Ways to assess ecological values and determine locations for aquaculture development have been proposed elsewhere, for example in relation to mussel aquaculture expansion in the Marlborough Sounds (e.g., DOC 1995; Forrest 1995). Similarly, overseas studies have described biological and physical (e.g., minimum depth, water currents) criteria for site selection in relation to salmon farming to minimise ecological effects (Levings et al. 1995).

3.1.4 Broader considerations of seabed effect

The discussion above focuses on waste feed and faecal deposition as the overriding factors influencing sediment-dwelling biota beneath and adjacent to finfish farm sites. While this has invariably been the case in the numerous studies of finfish farm impacts, broader effects of deposition, as well as other drivers of seabed impact, may also be important in certain circumstances.

New Zealand and overseas research to date has typically described ecological effects on the seabed based on infaunal communities as indicators. However, another important component of seafloor community is the assemblage of animals and plants that live on the sediment surface, which are commonly referred to as 'epibiota'. Depositional effects on epibiota from finfish farms in New Zealand are not well documented, although the Forrest (1996b) study referred to in the previous section provides one example where epibiota were observed beneath salmon cages in a well-flushed environment. Similarly, organisms such as sea cucumbers, cushion stars, and snake stars have been observed aggregating under conditions of mild enrichment at New Zealand salmon farming sites (Govier and Bennett 2007a), sometimes in association with bacterial mats. However these fauna appear to be displaced in situations of high enrichment. Epibiota may also respond to salmon farm effects other than direct deposition. For example, they may scavenge fouling biota that have fallen from (or been de-fouled from) the farm structures.

Deposition of fouling biota may also contribute to seabed enrichment. One example arises in situations where fouling organisms reach high densities on farm structures and fall to the seabed either naturally or because of deliberate defouling by farm operators. The fouling biomass may intermittently be a substantial component of the organic material deposited to the seafloor, as appears to be the case for the invasive sea squirt *Didemnum vexillum* at salmon farms in the Marlborough Sounds. In such situations, the deposited fouling biomass may exacerbate enrichment effects (at least in the short-term) associated with other processes.

Finally, direct effects on the seabed could, under certain conditions, arise via processes other than deposition alone. For example, shading from farm structures could reduce the amount of light to the seafloor. This in turn could reduce the productivity of ecologically important primary producers such as benthic microalgae, or beds of macroalgae or eelgrass, with a range of associated ecological effects (e.g., Huxham et al. 2006). This issue is unlikely to be important at present in New Zealand, but could conceivably arise if farms were located in environments of relatively high water clarity, especially in well-flushed locations where deposition effects were low. Hence, this is a site-specific issue, and one that can be effectively mitigated by appropriate site selection.

3.1.5 Seabed recovery

One of the ways in which the significance of human activities in coastal environments can be assessed is to consider whether they cause permanent or long-term changes, or whether adverse effects are reversible once their source is removed. This is a pertinent question to address in the case of new finfish farm developments, and has particular relevance for the evaluation of mitigation strategies based on farm fallowing and rotation (see Section 3.3.3).

Fish farm studies in New Zealand and overseas indicate timescales of recovery ranging from months to years. The rate largely depends on the spatial extent and magnitude of effects, and the flushing characteristics of the environment (Karakassis et al. 1999; McLeod et al. 2004); essentially larger and more heavily impacted sites, or sites in areas of relatively weak currents, take longer to recover. A number of overseas studies describe partial recovery within the first 3-6 months after the cessation of farming (Mazzola et al. 2000; Brooks et al. 2003; Macleod et al. 2006), but complete recovery (i.e., comparable to background conditions) can take many years and is often not fully realised in the timeframe of monitoring programmes (Karakassis et al. 1999; McGhie et al. 2000; Pohle et al. 2001; Pereira et al. 2004). The process tends to involve an initial improvement in the intensity of physico-chemical effects, with a slower timescale of recovery for seabed faunal communities (Pohle et al. 2001; Brooks et al. 2004; Macleod et al. 2004).

The best studied New Zealand example of seabed recovery is the Forsyth Bay salmon farm in the Marlborough Sounds, which was completely fallowed in November 2001 (i.e., all farming structures were removed). Prior to being fallowed, the sediments beneath the site were highly enriched, with extensive coverage of the seabed by bacterial mats, highly elevated organic contents and out-gassing at the water surface. Infaunal abundance and richness were both markedly suppressed, indicative of near-azoic conditions (Hopkins 2001). Since it has been fallowed, there has been a reduction in the magnitude of effects, including reduced sediment organic content, increased species diversity and abundance, and a corresponding decrease in the number of opportunistic species such as the polychaete *Capitella capitata*. In fact, during the latest Cawthron survey (December 2006), *Capitella capitata* and bacterial mats were both absent at the site (Govier and Bennett 2007b). These changes indicate a marked improvement in seabed health; however, the site is still enriched six years after being fallowed. Full recovery to pre-development conditions will require the complete breakdown of the residual, more recalcitrant organic materials, and these final stages are estimated to take another three or more years. However, recovery rates may be assisted by the progressive recolonisation of burrowing infaunal species, which help to irrigate the sediments, increasing flushing and oxygenation (Heilskov and Holmer 2001; Holmer et al. 2003; Heilskov et al. 2006).

3.1.6 Seabed effects and implications for finfish farm development in New Zealand

Knowledge of seabed effects beneath finfish farms containing species other than salmon are relatively uncommon, but the few overseas studies that do exist describe similar patterns of organic enrichment to that of salmon farming. Even where the magnitude of effects varies among species or with different farming techniques and other factors, it is likely that new finfish farms will result in marked localised physico-chemical and ecological changes to the seabed beneath them. Numerous existing studies, both from New Zealand and overseas, reveal that seabed effects rapidly decline with distance from farm cages, although low level changes can be evident tens of metres beyond the farm perimeter, and sometimes for several hundred metres in the direction of prevailing water currents. Such effects are reversible, although recovery may take many years in sheltered waters where most fish farming presently occurs in New Zealand. The magnitude of effects may be reduced, and recovery accelerated, where fish farms are positioned in high current environments or open coastal situations where wave action may contribute to flushing and dispersion of farm-generated wastes (Section 4.9). It is also possible to minimise effects by a reduction in factors such as stocking density, and by careful management of feed wastage.

Clearly, future coastal finfish farms in New Zealand are likely to result in localised effects on seabed species and habitats. From an ecological perspective, a key goal for future development should be to locate farms in areas where effects are minimised either because species and habitats of special value are not present, or where flushing characteristics alter deposition patterns to a point where significant adverse effects do not occur. In this respect, tools such as predictive depositional models (e.g., DEPOMOD; Cromey et al. 2000) can be useful in estimating the spatial extent and magnitude of effects prior to new developments. Seabed effects from individual farms can also be managed through the development of environmental criteria, which can be integrated into adaptive management plans, as has been the approach with salmon farming in the Marlborough Sounds (see Section 3.3.4).

3.2. Effects on the water column

3.2.1 Overview of issues

As caged fish farming expands globally, water column issues are receiving increasing attention (Crawford 2003; Read and Fernandes 2003). In a similar way to that described for seabed deposition, overseas studies show that finfish farms in areas with inadequate flushing and high stocking densities have the greatest potential for adverse water column effects (Wu et al. 1994; La Rosa et al. 2002). In New Zealand, water column effects have recently been considered in relation to salmon farming in the Marlborough Sounds (e.g., Hopkins and Forrest 2002; Hopkins 2004; Hopkins et al. 2004a). While these New Zealand studies have outlined a range of potential effects (e.g., reduction in water clarity), most are considered to be of minor significance. The only two issues to emerge that may be of particular relevance to finfish farm developments in New Zealand are:

- Depletion of dissolved oxygen (DO) in the water column.
- Nutrient enrichment of the water column.

Depletion of DO can occur within and around finfish farms due to the respiratory activities of the farmed fish and microbial degradation of waste materials in seabed sediments. This issue is of most significance to the farmed finfish stock although it may also be of ecological importance (see below). Excessive oxygen depletion in the water column could potentially stress or kill the fish and other animals (e.g., epibiota), with sediment DO depletion resulting in the release of toxic by-products (e.g., hydrogen sulphide) into the water, which can also have adverse effects on fish and other organisms as noted above. Significant depletion of water column concentrations of DO at finfish farms overseas has usually only occurred when cages are heavily stocked or where they are located in shallow sites with weak flushing (La Rosa et al. 2002).

In New Zealand, monitoring data from present salmon aquaculture operations reveal that water column DO concentrations do not get significantly depleted; maintenance of adequate DO levels is critical to the survival of the farmed stock, and is managed well at individual farms. In relation to future development in New Zealand, DO depletion is an issue that may need to be considered if, for example, multiple farms in close proximity are proposed. In such instances there is the potential for DO to become increasingly depleted as water currents pass through sequential farms (Rutherford et al. 1998). These types of risks could be avoided by appropriate spacing of sites.

From an ecological perspective, the most important water column issue that should be considered in relation to future finfish farm development in New Zealand is the potential 'eutrophication' effect of nutrient enrichment (e.g., Rutherford et al. 1988; Gillibrand and Turrell 1997; SEPA 2000). Eutrophication is the process where excessive nutrient inputs to a water body result in excessive algal growth and flow-on effects to the wider environment such as reduced water clarity, physical smothering of biota, or extreme reductions in DO because of microbial decay of the algal biomass (Degobbis 1989; Cloern 2001). In marine systems, an additional concern with water column nutrient enrichment is the potential for an increased occurrence of harmful algal blooms (HABs; Anderson et al. 2002; Yap et al. 2004). This includes blooms of species that produce biotoxins. Some biotoxins can be directly toxic to fish, and others can accumulate in shellfish and affect consumers, often leading to restrictions in harvesting shellfish. Salmon farming in New Zealand has not given rise to these types of effects, and such effects are unlikely in the near future unless considerable new development is anticipated. However, because of the general perception of the potential for eutrophication effects from finfish farming, the remainder of the water column discussion focuses on nutrient production by finfish farms and its ecological implications.

3.2.2 Nutrients in marine systems and contributions from finfish farms

Nitrogen (N) is generally considered a key nutrient that can limit plant growth in temperate coastal waters (Eppley et al. 1969; Weston 1990). Based on reported seawater ratios of nitrogen, phosphorus and silicate (N:P:Si), this is also the case for New Zealand coastal regions (MacKenzie 2004). As such, phytoplankton (drifting microscopic plants) are likely to be limited at certain times of year by the supply of dissolved inorganic N (DIN) rather than by the supply of other nutrients. Of particular significance in relation to fish farming, is the amount of N released during fish production, and especially DIN in the form of ammonium-N excreted by the fish stocks or released from locally enriched sediments (Schendel et al. 2004). Although nitrate also forms a component of DIN, ammonium-N is expected to be the dominant form of DIN output from finfish farms.

The overall contribution of N from a finfish farm can be viewed in a wider context by comparing mass loads with other point and non-point sources. Table 1 presents an example where this approach has been undertaken for salmon farm N inputs in the Marlborough Sounds. In this situation, it was estimated that approximately 60-73 tonnes of ammonium (which approximates DIN in this case) and 111 tonnes of total N (TN) would be discharged by a salmon farm of moderate size (i.e., typical of a salmon farm in the Marlborough Sounds). This estimate was based on a feed usage of 2000 tonnes per annum, a 1.5:1 feed conversion ratio and ammonium-N and TN excretion rates of 45-55 kg and 83 kg, respectively, per tonne of fish (Gowen and Bradbury 1987).

Table 1 Estimated mass load of nitrogen (tonnes/yr) from a typical Marlborough Sounds salmon farm compared with other sources and sinks (modified from Hopkins et al. 2004a).

Nitrogen source	Dissolved Inorganic Nitrogen (DIN)	Total Nitrogen (TN)
TYPICALMARLBOROUGH SOUNDS SALMON FARM [1]		
2000 tonnes feed usage	60-73	111
3000 tonnes feed usage	100-110	166
4000 tonnes feed usage	120-147	221
EXAMPLES OF MUNICIPAL AND INDUSTRIAL DISCHARGES [2]		
Bells Island municipal discharge (Richmond/Nelson)	NA	97.1
Nelson City municipal discharge	63.9	101.8
Nelson fisheries processing	18.6	70.4
RIVERINE AND MARINE INPUTS [3]		
Pelorus and Kaituna Rivers	500-600	
Net input from Cook Strait (to Pelorus and Kenepuru Sound)	12,000	
NITROGEN LOSSES		
Annual mussel harvest from Marlborough Sounds[4]		885

Notes:

1. These are estimates of total loading based on a 1.5:1 feed conversion rate and dissolved and total N outputs of 45-55 and 83 kg (respectively) per tonne of fish produced (Gowen and Bradbury 1987).
2. Figures for other treated wastewater discharges revised from those reported in Hopkins and Forrest (2002), using data from Marlborough District Council, Gillespie et al. (2001), and Barter and Forrest (1998).
3. Estimates from MacKenzie (1998).
4. Estimate is based on the 2006 harvest of 63,204 tonnes (green weight) and a 1.4 % per tonne conversion rate (MacKenzie 1998).

While this estimate is relatively simplistic, it suggests that a typical Marlborough Sounds salmon farm represents a source of 'new' N to the marine environment that is comparable to other typical point sources from human activities. Within the context of other major nutrient sources that include river inflows (which incorporate run-off from land-based sources such as agriculture and horticulture), seabed recycling and Cook Strait oceanic inflow, the 'new' N contribution from salmon farms is reasonably small, particularly when considering the wider Marlborough Sounds region. Furthermore, the removal of N from the system via the harvest of farmed mussels is estimated to more than compensate for the present level of loading from salmon farms in the Marlborough Sounds (Table 1), although the distribution of N must also be considered in specific situations to ensure against localised over-enrichment (see below).

3.2.3 *Implications of finfish farm development for nitrogen enrichment*

Finfish farming in New Zealand, to date, has been largely limited to salmon, with yellowtail kingfish currently a trial species. For these species, as well as for possible future candidates such as groper, we assume that any species-specific differences in nitrogen production will be less important than factors such as farm stocking density. Hence, the following discussion may be considered appropriate for existing finfish species in New Zealand and other pelagic species that may be farmed in the future using sea-cage technology.

Assimilative capacity of the receiving environment

There is no widely accepted guidance as to what constitutes an acceptable level of nitrogen input to coastal systems. In order to avoid over-enrichment (i.e., eutrophication), the input must not exceed the assimilative capacity of the receiving environment at local scales and more broadly. However, the assimilative capacity is a complex function of a system's biotic and abiotic characteristics and includes such factors as flushing rate, light and temperature regime, several nutrient cycling processes (e.g., microbial remineralisation and denitrification rates), and grazing pressure (Tett and Edwards 2002). The issue of assimilative capacity is further discussed in Section 4.10.2 in relation to the sustainability of finfish farming.

Phytoplankton and harmful algal blooms

Although there is general consensus that fish farms cause localised nutrient enrichment, the effects on phytoplankton communities in general (e.g., species composition and abundance) are not well understood for coastal waters (Frid and Mercer 1989; Wu et al. 1999; Wu et al. 1994; La Rosa et al. 2002). Monitoring results for salmon farms in the Marlborough Sounds and Big Glory Bay suggest that nitrogen concentrations sufficient to cause significant enrichment have not been reached as a result of farm inputs (Hopkins and Forrest 2004a; Section 4.10.2). Although within-cage nitrogen concentrations may become measurably elevated, these are likely to be diluted to near-ambient levels within a period of hours. In such instances we would not expect nutrient release from within the cages to stimulate development of phytoplankton blooms, as the generation time required for phytoplankton to respond is 1-3 days. Hence, at sites where flushing and mixing rates are sufficient to dilute locally elevated nutrient concentrations to near ambient levels before phytoplankton are able to reproduce, blooms are not likely to be generated.

In Scotland, Tett and Edwards (2002) concluded that there was no confirmed connection between harmful algal blooms (HABs) and finfish farming, and suggested that nutrient enrichment by fish farms would be insignificant unless the farm was located in an enclosed basin where water exchange was poor. In New Zealand, no link has been made between salmon farm nutrients and HABs. Where HABs have occurred in the vicinity of salmon farms their cause has been attributed to natural processes (Section 4.10.2). Similarly, phytoplankton monitoring in the Marlborough Sounds has not revealed an increased phytoplankton biomass or incidence of HABs in the vicinity of salmon farms (Hopkins et al. 2004a). While blooms of phytoplankton have been recorded and harmful species detected throughout the Sounds, these appear to be regional phenomena and driven by processes that are unrelated to salmon farming activities. Nonetheless, any nutrient discharge into a nutrient-limited environment will result in an increase in phytoplankton biomass. Where this enhanced production occurs over a wide area, is rapidly diluted, or mitigated by other forms of aquaculture (e.g., shellfish farming), it is unlikely to cause adverse effects. However, it is theoretically possible for incremental increases (i.e., in addition to those from other sources) in nutrient concentrations from finfish farms to affect the magnitude or duration of natural bloom events. The potential for such effects should be a consideration in the future development of fish farming in New Zealand, especially in the event that significant expansion is proposed.

3.3. Mitigation of seabed and water column effects

In most cases, the major factors affecting the magnitude of seabed and water column effects will be feed usage, finfish biomass per unit area, feed composition and feeding efficiency, water currents and flushing, and water depth. These factors can be influenced by appropriate initial site selection, and subsequent farm management practices, as described below.

3.3.1 Site selection

Seabed and water column effects can be minimised by locating farms in areas having sufficient flushing to facilitate dispersion and assimilation of farm wastes. Depositional effects on the seabed can be mitigated by locating farms in areas where species and habitats of special value are not present, or where flushing characteristics alter deposition patterns to a point where adverse effects do not occur. Two main strategies for the latter approach, discussed by Forrest (2001) in relation to Marlborough Sounds salmon farms, are:

'Concentrate and contain': Place finfish farms in low current environments where seabed effects will be pronounced but highly localised. The disadvantages are that seabed conditions may deteriorate to a point where sediment-dwelling organisms are completely excluded, and seabed recovery is relatively slow if the cages are removed. Furthermore, there is potential for the farm to become 'self-polluting', with poor water quality and sediment health resulting in adverse effects on the farmed fish stock.

'Disperse and dilute': Place farms in well-flushed environments where seabed and water column effects may be of relatively low magnitude but more widely dispersed. The main disadvantage with this approach is that, while physico-chemical effects may be lower, well-flushed areas (e.g., areas with strong water currents) can have ecological values of special significance (DOC 1995). Hence, from a production perspective, well-flushed environments are likely to be preferred, but from an ecological perspective the significance of effects will invariably be site-specific.

3.3.2 Feed control

Reduction in feed wastage can have substantial benefits for seabed quality beneath salmon farms, and hence the quality of the overlying water. This has been evident at Marlborough Sounds salmon farms where early monitoring revealed significant feed wastage and strong enrichment effects (e.g., Forrest 1996a), leading to a number of management responses that resulted in improved seabed conditions, mainly:

- Advances in automated salmon feeders (shut-off signals linked to underwater cameras that detect waste feed), resulting in significantly less waste feed reaching the seafloor.
- The use of higher quality feed and improvement in feed conversion ratios (a measure of dry fish weight input to wet fish weight output), meaning that less food is needed to grow the same amount of fish.
- Employment of overseas managers to access additional technical expertise, aimed at reducing feed wastage.

These types of strategies may also mitigate effects on wild fish populations and other organisms that are influenced directly (via waste feed consumption) or indirectly (e.g., via the food chain or fish aggregation) by feed wastage.

3.3.3 Rotation of sites to allow seabed fallowing and recovery

In theory, the magnitude of seabed effects can be managed by rotating cages among different locations, by moving cages before a farm site becomes excessively enriched and uninhabitable to sediment-dwelling organisms. The benefits of fallowing and cage rotation have been demonstrated (to a limited extent) overseas at sites where seabed recovery can occur within < 6 months (e.g., Brooks et al. 2003). Other overseas examples, and experience at salmon farm sites in the Marlborough Sounds, indicate that seabed recovery may take many years (e.g., Section 3.1.5), whereas enrichment effects can become well advanced within a matter of a few months (and perhaps weeks) from the time a farm is stocked (Hopkins 2001; B. Forrest, unpubl. data). Under such conditions, the operation of a single farm using this approach would require numerous sites, leading to cumulative effects across a relatively large area of seabed. In this case, it is arguably preferable to accept that the seabed can be substantially modified beneath fish farms, and restrict effects to a single location where the 'loss' of seabed values is considered acceptable to stakeholders. However, this view does not necessarily preclude fallowing and rotation as a future management strategy in New Zealand, for example if finfish farms are developed in well-flushed areas where seabed effects are minimal and recovery occurs within a short time-frame. Cage rotation may also be necessary from an operational perspective, for example to break a disease cycle or for single year class farms, or if seabed enrichment and associated water column effects led to adverse effects on fish health.

3.3.4 Monitoring and adaptive management

Ecological effects on the seabed from individual farms can be managed through the development of environmental criteria, which are integrated into adaptive management plans. This approach, which is in part based on zones of impact defined for salmon farming off the Scottish coast by Brown et al. (1987), has been adopted for salmon farms in the Marlborough Sounds (Hopkins et al. 2004). The approach specifies the spatial extent over which defined levels of seabed impact are permitted, as described in Table 2 and visually depicted in Figure 7.

Table 2 Description of environmental criteria for effects zones and their permitted spatial extent, which are used to manage seabed effects at Marlborough Sounds salmon farms.

Zone	Environmental criteria	Permitted spatial extent
1	Sediments are anoxic and azoic (i.e., sediment-dwelling organisms are absent).	These conditions are not permitted beneath any farm.
2	Sediments become highly modified, containing a low species diversity and dominated by opportunistic taxa. It is expected that a gradient will exist within this zone, with higher impacts present directly beneath the cages.	Beneath the cages and out to 50 m from their outside edge.
3	A transitional zone between zones 2 and 4. Within this zone, some enrichment and enhancement of opportunistic species may occur; however, species diversity remains high with no displacement of functional groups. It is expected that a gradient will also exist within this zone.	From 50 m to 150 m from the outside edge of the cages.
4	Normal conditions (i.e., background or control conditions).	Beyond 150 m from the outside edge of the cages.

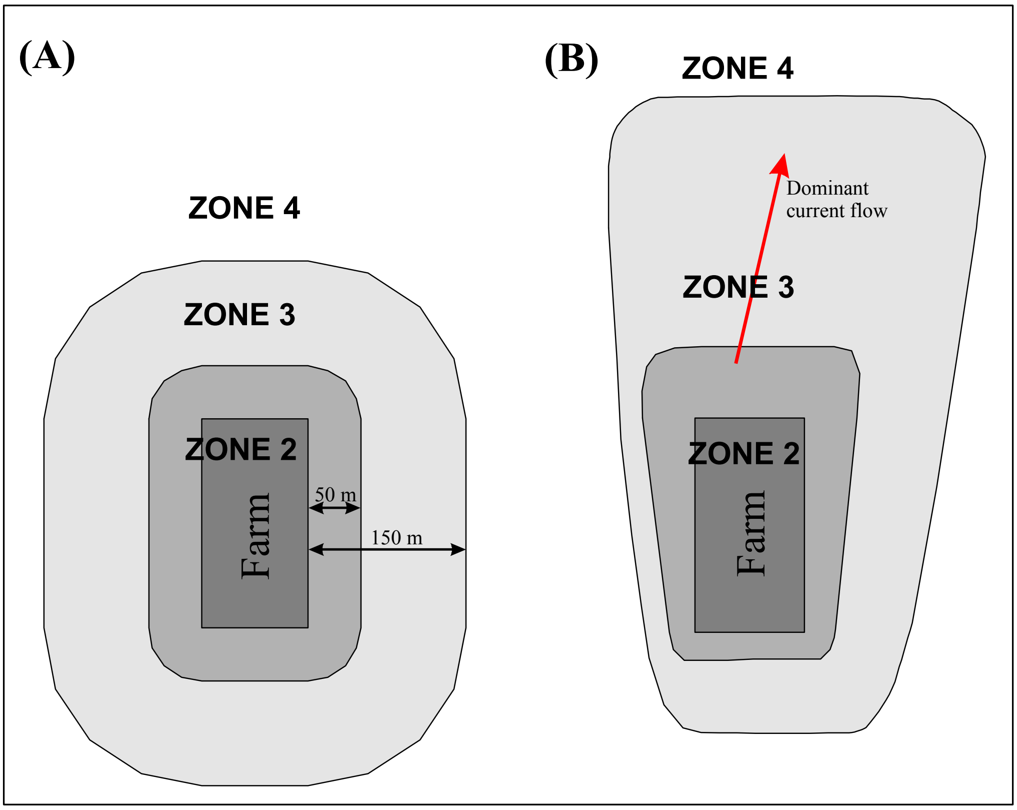


Figure 7 Development of zones of acceptable seabed effects from finfish farms. (A) conceptual approach based on assumption of uniform waste distribution; (B) hypothetical adaptation of the effects zones to site-specific environmental conditions.

In relation to the Marlborough Sounds situation, these zones and their spatial extent are based on consensus reached among stakeholders as to an acceptable level of impact. Definition of the size of the effects footprint is initially based on the simplistic assumption that the spatial extent of farm influence is similar in all directions from the cages (Figure 7A). In reality, however, the seabed footprint will be skewed according to the direction and strength of prevailing water currents (Figure 7B), hence the zones can be modified to reflect site-specific conditions and to ensure that species or habitats of special value (e.g., nearshore rocky reef areas) are not adversely affected.

Provided the placement of the zones and their associated environmental quality criteria are agreed to by all parties, this method can provide a useful basis for monitoring. It gives transparency and certainty to all stakeholders, and provides the industry flexibility to change farm operations to suit site-specific conditions, provided they can demonstrate compliance with the environmental criteria. For Marlborough Sounds salmon farms, compliance is assessed via annual monitoring of seabed effects using physico-chemical and ecological indicators such as those outlined in Section 3.1.2, and farm management adapted according to monitoring findings. This adaptive approach is relatively common in fisheries management, and is becoming increasingly common within the marine farming industry, for example in relation to mussel spat-catching in Tasman and Golden Bays (Hopkins and Robertson 2002), mussel farming in the Firth of Thames (Turner and Felsing 2005), and salmon farming in Tasmania (Crawford 2003).

3.3.5 Other seabed and water column mitigation approaches

The measures described above outline what we believe to be the most widely used and best available tools for management of seabed and/or water column effects in New Zealand. For completeness, we have described below some additional mitigation measures from overseas studies that could be implemented in New Zealand if technically feasible. Examples include:

Collection of organic wastes before they reach the seabed or physical remediation of impacted sediments: Various solutions have been proposed or trialled overseas to reduce the extent of organic enrichment below net cage aquaculture systems, including: collection of particles falling to the seabed, deployment of artificial reefs beneath cages to process farm waste before deposition, collection of detritus from the seabed using submersible pumps, and harrowing of enriched seabed sediments to enhance oxygenation and organic matter processing. Most of these solutions appear to be impractical or have no demonstrable net environmental benefit (Angel and Spanier 2002).

Microbial and chemical remediation: Bio-augmentation (the addition of a mixture of bio-fixed bacterial species) and bio-stimulation (the addition of oxygen release compounds) techniques have been trialled experimentally as means of enhancing the rate of decomposition of organic matter in sediments beneath fish farms overseas (Vezzulli et al. 2004). Although the trials indicated potential for enhancing recovery rates in organically enriched sediments, the methods have not yet been tested on a larger farm scale. Further research will be required before their applicability as remediation tools for New Zealand finfish farms can be confirmed.

Modification of farm design to reduce the severity of seabed effects: It may be possible to alter the orientation and layout of the cages and the mooring configuration to minimise interaction with sensitive habitats. Similarly, single point moorings (similar to a vessel swing mooring) have been proposed as a means of spreading seabed effects over a greater area than achieved for finfish farms with fixed moorings (Goudey et al. 2001). The efficacy of this method in reducing seabed effects was recently demonstrated overseas for a deep water (230 m) fjord site (Kutti et al. 2007). Based on New Zealand experience in relatively shallow (30 – 40 m) nearshore areas, however, approaches that spread seabed effects across a wider area would be unlikely to have any substantial ecological benefits, and potentially lead to wider environmental issues (e.g., navigation and safety concerns).

Co-culture/polyculture: The concept behind co-culture or polyculture is to grow aquaculture species together or in close proximity to achieve enhanced production, while at the same time reducing environmental effects. For example, through the uptake of ammonium and production of oxygen through photosynthesis, seaweed culture can greatly reduce adverse water column effects (Petrell and Alie 1996). The benefits of other integrated systems have also been discussed in overseas studies, such as fish-bivalve co-culture (e.g., Lefebvre et al. 2000) and fish-seaweed-abalone polyculture (e.g., Neori et al. 2000).

Although the concept is theoretically sound, the benefits of co-culture or polyculture with respect to mitigation of finfish aquaculture effects have not been demonstrated in New Zealand through practical application. Nonetheless, interest in the potential of co-culture or poly-culture techniques, as a means of mitigating discharge-related effects whilst increasing production, has intensified over recent years. In New Zealand, interest in fish-bivalve co-culture is of particular interest, reflecting the relative size and importance of the mussel industry. Hence, co-culture could involve growing mussels (or other filter-feeding bivalve shellfish such as oysters or scallops) along-side, or in the general vicinity, of finfish cages. The increased availability of nutrients in the vicinity of a fish farm has the potential to increase phytoplankton production, which is the primary food source of bivalve shellfish. The culturing of filter-feeding bivalves, on the other hand, removes phytoplankton and waste-generated particulate materials from the water column thus lessening the potential for seabed enrichment or phytoplankton blooms (see Section 3.2.2). Hence there is potential for integrated culture to increase the productivity of a shellfish farm while reducing nutrient loading and particulate wastes from a finfish farm (Cheshuk et al. 2003).

The relative positioning of the co-culture components is important for capturing the joint benefits. Some overseas studies have shown that an appreciable increase in bivalve growth can occur surrounding finfish farms (Wallace 1980; Jones and Iwama 1991). Other overseas studies have found that shellfish cultured within finfish farm sites did not have significantly different growth or production rates compared to those cultured at distant sites (Cheshuk et al. 2003; Taylor et al. 1992; Parsons et al. 2002). In relation to a proposed finfish farm development in the Marlborough Sounds, Keeley et al. (2007) suggested that, in order for a shellfish farm to remove waste particulates from a finfish farm, the two would have to be sited close together (i.e., ~100 m apart or less).

4. WIDER ECOLOGICAL ISSUES

4.1. Overview

Effects on the seabed and, to a lesser extent the water column, have been a focus for much of the research undertaken to date on finfish farm effects. Increasingly, however, other ecological effects from finfish aquaculture are also recognised, not all of which are well understood. Furthermore, whereas seabed and water column effects are of significance to all developments, some of the broader ecological issues may only be relevant to particular species or locations, which means it is difficult to predict or prioritise what may be most relevant or important in the future. Nonetheless, in all cases the issues discussed below have the potential for wider ecosystem effects, whose significance will be related to the scale (i.e., local intensity and geographic distribution) at which finfish farming is developed in New Zealand. Except for a few instances where we note relevant New Zealand work, much of the discussion below relates to potential effects of finfish farms that can be inferred from overseas studies.

4.2. Habitat creation

Marine farms and other artificial structures in marine environments provide a three-dimensional reef habitat for colonisation by fouling organisms and associated biota, suspended above natural areas of seabed that are relatively two-dimensional. By comparison with natural rocky or soft-sediment habitats, such structures provide a substantial surface area for the attachment of fouling organisms (see photographs in Section 4.4). Overseas studies show that artificial structures can support a considerably greater biomass and density of organisms than adjacent natural habitats (e.g., Dealteris et al. 2004). Studies from New Zealand and overseas indicate the dominant groups on such structures include macroalgae and sessile (attached) filter-feeding invertebrates such as sea squirts, bryozoans and mussels (e.g., Hughes et al. 2005; Braithwaite et al. 2007). These assemblages typically have a range of other non-sessile animals associated with them, such as polychaete worms and various small crustaceans. Based on research conducted overseas, it appears that the assemblages that develop on artificial structures can be quite different to those in adjacent rocky areas (Glasby 1999; Connell 2000).

Artificial structures are recognised as providing foraging habitat, detrital food sources, breeding habitat, and refuge from predators for some species (e.g., Dealteris et al. 2004). The significant filtration and biodeposition capacity of sessile filter feeding communities associated with artificial structures is also well recognised (e.g., Hughes et al. 2005), but the ecosystem effects of such processes are not well understood. In relation to finfish farms in New Zealand, the functional role of the associated fouling community is unknown, but we would expect it to contribute in some way to the water column and seabed effects that were described in Section 3. Overseas studies show that the filtration capacity of extensive fouling communities has the potential to deplete phytoplankton and other particulates from the water column (Mazouni et al. 2001), potentially reducing enrichment effects in the case of finfish farms (Angel and Spanier 2002). On the other hand, biodeposits (faeces from consumed food and pseudofaeces from unprocessed food) produced by the fouling community have the potential to exacerbate seabed enrichment. A number of other aspects are also acknowledged, such as the role of artificial structures in the spread of fouling pests (e.g., Airoldi et al. 2005; Bulleri and Airoldi 2005; Forrest et al. 2007) as discussed in Section 4.4.

4.3. Effects on wild fish

The effects of habitat creation described above have the potential to increase fish abundances (e.g., Relini et al. 2000; Caselle et al. 2002; Dempster et al. 2004, 2006). Artificial structures are known to provide shelter, habitat complexity and a food source for small fish, as indicated by overseas work (Relini et al. 2000; Caselle et al. 2002) and a recent study of fish interactions with mussel farms in New Zealand (Morrisey et al. 2006a). Similarly the aggregation of fish around artificial structures is well recognised, and is sometimes used overseas as a basis for aggregating pelagic fishery species for capture (e.g., Buckley et al. 1989). Present evidence from international studies suggests that structure morphologies can be strongly species-specific, with different fish benefiting from particular structure types (Caselle et al. 2002). Aggregation of wild fish may also occur in response to artificial submerged lighting in sea-cages, but in relation to salmon farming in New Zealand this occurrence has been considered a highly localised influence of minor ecological significance (M. Porter, unpubl. report).

In the case of finfish farms, it is not only the structures and associated fouling communities that are important to wild fish species, but also the waste feed that can be generated. Wild fish on the outside of cages may feed on waste feed pellets that pass through the cage. Additionally, inside the cages, populations of small fish may be supported by the smaller feed particles, or ‘dust’, that is a waste component of most feeds. The extent to which such processes operate in New Zealand is unknown, but is likely to be limited given that feed wastage is closely managed, as described in Section 3.3.2. In New Zealand, various shark species have been described in the vicinity of salmon cages, and are possibly present to scavenge for mortalities or predate on aggregations of wild fish (NZKS 2006).

Fish that aggregate around cages overseas have been shown to have altered physiological condition, tissue fat content, and fatty acid composition compared to their wild counterparts (summarised in Dempster and Sanchez-Jerez 2007). Recent international studies have even suggested that finfish farming can increase regional fish biomass and promote the conservation of wild stocks, even beyond the immediate vicinity of the cages (Dempster et al. 2004, 2006; Machias et al. 2004). By consuming waste feed and assimilating nutrients, wild fish aggregations have the potential to ameliorate seabed effects beneath fish farms (Felsing et al. 2004; Dempster et al. 2005). In studies from western Australia (Felsing et al. 2004) and the Mediterranean (Vita et al. 2004), wild fish have been shown to reduce the amount of feed that reaches the seabed by as much as 60-80%. Additionally, any feed that does reach the seabed may be quickly consumed by bottom feeding fish (Thetmeyer et al. 2003). Other possible effects of farmed fish on wild fish populations include:

- Genetic and disease transfer between caged and wild fish, and ecosystem effects (see Section 4.7).
- Increased vulnerability of wild fish to recreational fishing, through aggregation.

- Reduced exposure to commercial fishing. Clusters of sea-cage finfish farms, for example, may act as small pelagic marine protected areas (Dempster et al. 2002).

The extent to which wild fish populations are enhanced may be difficult to separate from effects associated with the changes in fishing pressure that may occur as a result of finfish farms. These issues will need site-specific consideration as part of future finfish farm development in New Zealand. Particular interest is likely to arise where existing shellfish farms are converted to finfish farms. With respect to recreational fishing, for example, increased catches of species such as snapper (*Pagurus auratus*) are often reported with proximity to mussel farms, in part reflecting aggregation of snapper to feed on the mussel stock. Similarly, other popular recreational fish such as blue cod (*Parapercis colias*) can be caught beneath mussel lines in some regions (Gibbs 2004). The nature of the farm stock and the magnitude of seabed effects beneath fish farms (compared with mussel farms) means that these values are likely to change. While it is beyond the scope of our report to address such issues, they may need to be considered in the future.

4.4. Biosecurity risks and biofouling pests

4.4.1 Overview of issues

Human activities in New Zealand coastal areas are a significant mechanism for the dispersal of marine pests, particularly the movements of recreational and commercial vessels, and aquaculture activities (Dodgshun et al. 2007). Internationally, the role of aquaculture in the spread of fouling pests has long been recognised (Perez et al. 1981; Bourdouresque et al. 1985; Wasson et al. 2001; Leppäkoski et al. 2002; Hewitt et al. 2004). Awareness of this issue in New Zealand was largely precipitated in the late 1990s by concerns regarding the human-mediated spread and ecological effects of the Asian kelp *Undaria pinnatifida* (Sinner et al. 2000). Around this time, fouling also became recognised as a significant threat to aquaculture when a population explosion of the sea squirt *Ciona intestinalis* resulted in the mussel crop losses in parts of the Marlborough Sounds. Subsequently, other fouling pests have emerged whose potential for adverse effects on the aquaculture industry and the wider ecosystem have been recognised, such as the sea squirts *Styela clava* and *Didemnum vexillum* (Figure 8; Coutts and Forrest 2005, 2007). While many of these pest organisms have reached problematical densities only on artificial structures in New Zealand, overseas evidence also reveals their potential to be highly invasive in natural habitats (e.g., *Didemnum*; Bullard et al. 2007).

4.4.2 Spread of fouling pests via aquaculture

The propensity for aquaculture activities to spread fouling pests arises from the fact that suspended cultivation methods, and their associated structures and materials (e.g., ropes, floats pontoons), provide ideal habitats that allow such organisms to proliferate at high densities (e.g., Clapin and Evans 1995; Floc'h et al. 1996; Carver et al. 2003; Lane and Willemsen 2004; Coutts and Forrest 2007). From a biosecurity perspective, and for finfish farming in particular, ecological risks arise because the infested farm or other structures act as a 'reservoir' for the further spread of the pest.

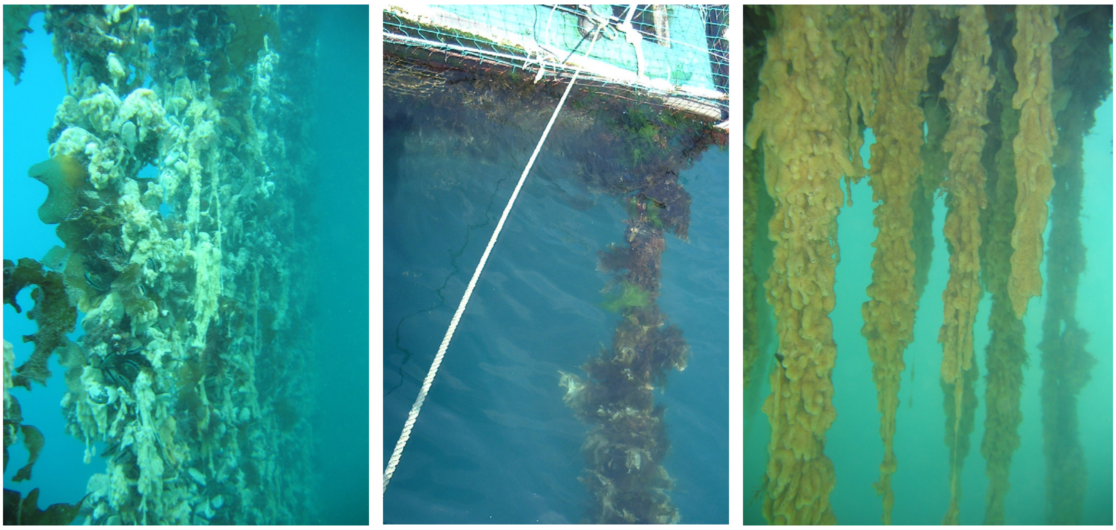


Figure 8 Fouling on artificial structures in the Marlborough Sounds. Left: *Didemnum vexillum* and *Undaria pinnatifida* on mussel crop lines (B. Forrest, Cawthron); middle: pontoon and anchor warp of a salmon farm (G. Hopkins, Cawthron); right: colonies of *Didemnum vexillum* droop 3 m beneath a floating pontoon (B. Forrest, Cawthron).

At local scales (e.g., within bays), spread from infested reservoirs is facilitated by microscopic life-stages (e.g., seaweed spores or animal larvae) that are released by adult populations and drift with water currents as part of the plankton. For some species dispersal can also occur via the drift of reproductively viable fragments (e.g., Forrest et al. 2000; Bullard et al. 2007). These types of processes can lead to the establishment of the pest on adjacent structures such as other marine farms, jetties and vessel moorings. In this way such structures can act as 'stepping stones' for the spread of pest species (Bulleri and Airoldi 2005).

For many fouling organisms, however, natural dispersal is limited, and spread across large areas or between regions occurs via inadvertent transport with human activities. For example, infested structures deployed at a marine farm (e.g., ropes, floats, pontoons), or temporarily associated with it (e.g., vessels), may be transferred to other localities as part of routine aquaculture operations. There is a high likelihood that associated fouling organisms will survive where such transfers occur without the application of measures to reduce biosecurity risks (Forrest et al. 2007). In recognition of this, the salmon farming industry in New Zealand, along with other aquaculture sectors, has been proactive in the development of biosecurity management measures, as described below.

4.4.3 *Present and potential biosecurity risks from finfish farming in New Zealand*

The risk of inter-regional spread of pest organisms by present finfish farm activities in New Zealand is low. A different company operates within each of the main salmon farming regions and there are generally no transfers between them. Where cages have been transferred historically, they have been completely refurbished (water or sand-blasted and repainted) before re-deployment (Forrest and Blakemore 2002). Within regions such as the Marlborough Sounds, however, transfers of equipment have occurred, in some instances leading to biosecurity risks. For example, the sea squirt *Didemnum vexillum* was inadvertently moved on salmon farm pontoons to a mussel growing area of Queen Charlotte Sound, and subsequently spread via natural dispersal from the salmon farming site to an adjacent mussel farm, resulting in crop losses (Coutts and Forrest 2007).

With respect to new finfish farming operations, biosecurity risks from fouling pests will be most significant when: (i) pest organisms are dispersed by finfish farm activities into regions or habitats that are optimal for their establishment and where they do not already exist; and (ii) finfish farming activities are the primary mechanism for the spread of the pests. If a pest organism is already present in the new habitat, or is likely to spread there regardless of finfish aquaculture activities, for example via natural dispersal or via non-aquaculture vectors (e.g., recreational vessels), then the incremental risk posed by finfish farm operations may be negligible. Determination of such risks is situation-specific hence must be evaluated on a case-by-case basis. Given a knowledge of the biological attributes of pest organisms (e.g., natural dispersal capacity and habitat requirements) and human-mediated pathways of spread, however, various assessment procedures can be used to assist with identification of relative risks and the extent to which they can be managed (e.g., Forrest et al. 2006).

Note, finally, that whereas the above discussion has focused on fouling as the primary biosecurity issue, additional biosecurity risks may be associated with finfish developments for new species. One example would be if the farm was stocked with fish that were reared in marine hatcheries in other regions, and transported to the farm site in raw seawater. In such cases, planktonic life-stages of pest organisms known to be present in the source region have the potential to be inadvertently transported to the farm site. Provided these and any other potential issues are recognised, however, appropriate management strategies could be implemented to reduce biosecurity risks. Furthermore, note that these risks are presently addressed for salmon and kingfish as part of a fish transfer authorisation process, in which industry must obtain permission from the Ministry of Fisheries before undertaking any such transfers (M. Gillard , New Zealand King Salmon, pers. comm.).

4.4.4 Biosecurity management and fouling pest control

There are a number of ways in which fish farm companies can contribute to the effective management of fouling pests. They can:

- Identify existing and future pests that threaten the aquaculture industry, and develop coordinated response plans for high risk species before they become established.
- Prevent incursions of new pests onto aquaculture structures. For vectors of spread such as service vessels, this could include maintenance of effective antifouling coatings, hull inspections to check for the presence of target pests, and hull cleaning as necessary.

- Eradicate pests from farm structures before they become well-established. This approach may only be worthwhile if the risk of reinvasion can be managed, and pests can be detected before they become widespread (Coutts and Forrest 2007).
- Contain the further spread of pests from infested aquaculture structures if eradication is not possible. Fouling could be reduced to a level that minimises the risk of natural dispersal to other vectors (e.g., vessels) or nearby structures, and pests could be eliminated from aquaculture vectors (equipment, vessels) before transport to other regions.

A range of tools, methods and knowledge are available from studies in New Zealand that would assist in these types of management approaches (e.g., Forrest et al. 2006; Coutts and Forrest 2007; Forrest et al. 2007). The key to whether they can be effectively used to manage biosecurity risks hinges in part on whether there is sufficient buy-in from other coastal operators and government agencies. Attempts by the aquaculture industry to deal with pests may ultimately be futile if such efforts do not have the support and participation of key stakeholders at a regional and national level.

4.5. Effects on seabirds

New resting space afforded by sea-cages and the increased fish activity in the immediate vicinity tends to attract, and possibly benefit, some bird species (Lalas 2001), although such relationships are not well understood. In New Zealand, sea-cages are likely to attract a variety of predatory seabirds, such as common shag species, gannets and gulls. These species may benefit from food sources provided by any small pelagic fish species (e.g., juvenile yellow eyed mullet, mackerel) that are attracted to the sea cages.

A previous New Zealand study that examined possible effects to King shags from the development of a large mussel farm concluded that the most commonly anticipated negative effects (i.e., entanglement and avoidance of feeding grounds due to increased boat traffic), were largely unfounded (Lalas 2001). Instead, Lalas (2001) concluded that the King shags may actually benefit from a new and additional food source. However, these findings may not be directly applicable to finfish cages as they have different structural configuration (e.g., surface nets) and prey assemblages.

A more recent New Zealand report also raises the issue of lost feeding habitat for King shags in areas where marine farms affect their seabed food sources such as flounder (Butler 2003). There appears to be too little information to establish whether this is a significant risk, and whether other factors (e.g., fish aggregation in the vicinity of fish cages; Section 4.3) mitigate any adverse effects by providing an alternate food source. If adverse effects do occur, then their significance will depend on the spatial scale of finfish farming in relation to the distribution and abundance of prey items. For individual farms, the potential for any adverse effects could probably be mitigated by appropriate site selection.

4.6. Effects on marine mammals: seals, dolphins and whales

4.6.1 Overview of issues

New Zealand fur seals are a prevalent and commonly problematic predatory species around salmon farms. Seals almost undoubtedly benefit from the additional food supply and haul out points that are afforded by most sea-cages. Their behaviour however, can cause major problems for farmers through direct predation, destruction of gear, fish escapements through damaged nets, and reduced fish growth and performance (Kemper et al. 2003; M. Gillard, New Zealand King Salmon, pers. comm.). As a consequence, salmon cages in the Marlborough Sounds, for example, are surrounded by predator nets that are designed to prevent seal access to the fish stock and the farm structures (Figure 9).

Entanglement of seals and dolphins in predator nets has been minimal and well-managed to date within the New Zealand salmon industry, but is an issue that should be addressed in relation to future finfish farm developments. Similarly, although habitat exclusion is not a significant issue given the small scale of the New Zealand finfish industry, overseas experience with this issue in relation to cetaceans (i.e., dolphins and whales; Kemper and Gibbs 2001; Kemper et al. 2003; Heinrich and Hammond 2006) suggests that it should be considered in relation to any large-scale future developments in New Zealand. Hence, the discussion below focuses on both entanglement and habitat exclusion. While the potential for wider ecosystem effects on marine mammals (e.g., food web interactions) is also recognised, these types of interactions and their actual or potential significance are yet to be documented.

Figure 9 Predator nets around Marlborough Sounds salmon farms (G. Hopkins, Cawthron).

4.6.2 Entanglement

Incidences of seal or cetacean entanglement are very few in New Zealand despite over 25 years of sea-cage salmon farming and the attraction of seals to sea-cages as described above. There are two reported incidences of seal entanglement and drowning at salmon farms, one of which involved a seal being caught beneath a predator net resting on the seabed and another being caught between the predator net and salmon net (A. Baxter, Department of Conservation Nelson, pers. comm.). Two cases of dolphin entanglement and death have been reported in New Zealand, both from the Marlborough Sounds (M. Aviss, Department of Conservation Picton, pers. comm.). In one, an unidentified dolphin species became trapped while a predator net was being replaced, and in the other case, a Hector's dolphin became trapped under a predator net. Through a joint process involving the industry and Department of Conservation, net design and operational practices for changing predator nets have been improved to minimise the risk of such occurrences (see Section 4.6.4). Internationally, fatal entanglements of dolphins in predator nets of finfish farms have been reported from Australia (Kemper and Gibbs 2001; Kemper et al. 2003) and Italy (Díaz López and Bernal Shirai 2007). This may reflect attraction of dolphins to a food source (Kemper and Gibbs 2001) as described in Section 4.3 for wild fish, although such interactions between finfish farms and cetaceans have not been proven (Kemper et al. 2003).

4.6.3 Habitat exclusion

As noted in Section 4.6.1 above, habitat exclusion is not presently a significant issue considering the small size of the New Zealand finfish industry. While there is some overlap with cetacean habitat, very little of this occurs in what may be described as 'critical habitat' (S. Du Fresne, Du Fresne Ecology Ltd, pers. comm.). By contrast, spatial overlap between aquaculture and small cetacean habitat is extensive in parts of Chile where finfish farming is relatively extensive (Kemper et al. 2003; Heinrich and Hammond 2006). Some authors have reported that Chilean dolphins may now be excluded by salmon farms from bays and fiords they traditionally used (Reeves et al. 2003). Hence, although significant competition for space in New Zealand seems unlikely, should the scale of finfish farming substantially increase, then this situation may change. It will therefore be important that farm locations are carefully selected so as to minimise the potential for adverse effects.

Exclusion of cetaceans from areas containing fish farms can also potentially occur indirectly through the use of acoustic deterrent/harassment devices (ADDs or AHDs), which are sometimes used at overseas farms to dissuade seals from feeding on farm stock. Exclusion has been reported overseas for killer whales (Morton and Symonds 2002) and harbour porpoises (Olesuik et al. 2002). ADDs have been trialled at New Zealand finfish farms but are currently not in use because they were unsuccessful. Internationally some authors have suggested that ADDs could act as a 'dinner bell', alerting animals to the presence of a food source (Würsig and Gailey 2002). However, the intermittent use of ADDs may be relatively effective, and provide an additional strategy to minimise risks (e.g., of entanglement) associated with activities such as predator net changing. The use of ADDs at any point in the future in New Zealand would require approval from the Department of Conservation under the Marine Mammals Protection Act.

4.6.4 Managing adverse effects on marine mammals

Marine mammal entanglement and habitat exclusion have been relatively minor issues at New Zealand finfish farms to date, and both can be effectively managed. The issue of habitat exclusion can be dealt with on a case-by-case basis, by selecting farm locations to minimise the potential for space competition with marine mammals. Entanglement risks can be minimised by adopting measures such as enclosing predator nets at the bottom, keeping nets taut, using mesh sizes of < 6 cm (Kemper et al. 2003), and keeping nets well maintained (e.g., repairing holes). These types of design and maintenance features, and operational procedures for changing nets that minimise entanglement risk, have already been implemented at New Zealand salmon farms. Similarly, efforts to reducing feed waste described in Section 3.3.2, will minimise fish aggregation, which may also reduce the amount of time some species (e.g., dolphins) spend near finfish farms.

4.7. Genetics, diseases and effects of escaped fish

4.7.1 Overview of issues

In any finfish aquaculture operation, there is potential for interaction between farmed and wild fish populations. These include: (i) competition for resources with wild fish, and related ecosystem effects (e.g., through predation) from escapee fish; (ii) alteration to the genetic structure of wild fish populations by escapee fish; and (iii) transmission of pathogens (diseases and parasites) from farmed stocks to wild fish populations (Gillanders and Joyce 2005). Atlantic salmon escapes in the northern hemisphere, for example, have occurred on such a large scale that most of the wild catch is now thought to be sourced from farmed stock (Gausen and Moen 1991; Lund et al. 1991; Hansen et al. 1999). Interbreeding resulting from such interactions can result in changes of allele frequencies and the introduction of new genetic material, both of which can influence the 'fitness' of wild populations. While these types of risks have been highlighted in many overseas studies (primarily in relation to salmon farming), they do not appear to be significant issues for New Zealand at present, and it is likely that any adverse effects from future development can be effectively managed. We expand further on these issues in subsequent sections.

4.7.2 Escapee effects and genetic influences on wild stocks

Ecosystem effects and genetic influences from escapee fish are likely to be relatively minor in New Zealand. Effects from escapee salmon, for example, are likely to be minimal given the relatively small scale of the industry, and due to limited salmon numbers in the wild populations within existing grow-out regions. Furthermore, the wild populations are non-indigenous, hence genetic effects from salmon are arguably of less importance than in the case of aquaculture of native finfish species. For species such as kingfish, and other candidate species that may be trialled in New Zealand, significant ecosystem effects from escapees are unlikely, especially given that fish escapes can be minimised through adherence to appropriate management practices.

For kingfish, significant genetic influences on wild stocks are unlikely. Kingfish are an abundant pelagic species that can travel long distances, to the extent that there is some mixing of the Australian and New Zealand stocks (Gillanders et al. 2001; Nugroho et al. 2001). Such a wide geographic distribution is consistent with weak genetic structuring (or inter-population differences), and therefore a low susceptibility to genetic influences from farmed fish. Furthermore, the industry plans to breed from wild-sourced kingfish brood-stock, which will assist in reducing genetic risks to wild populations (Gillanders and Joyce 2005), along with appropriate spawning protocols and management measures that are aimed at maintaining genetic diversity in farm stock. Genetic risks from other candidate species will need to be assessed on a case-by-case basis.

The New Zealand situation contrasts with overseas salmon industry experience where interbreeding between escapees and wild salmon can adversely affect native populations through long-term genetic changes (McGinnity et al. 1997). This arises because farmed fish are often bred from a small gene pool for selected traits (e.g., fast growth) that can result in genetic divergence from the wild stock (Fleming et al. 1996; Einum and Fleming 1997). For example, escaped fish can have reproductive and survival deficiencies (Youngson et al. 2001) that may be passed on to wild fish through interbreeding (Cross 2000). Alternatively, fast growth rates and aggressive behaviour in escaped fish can give them a competitive advantage over wild fish in pairwise contests (e.g., when breeding; Einum and Fleming 1997), thereby promoting further suppression of wild traits.

The key factors that determine the likelihood that wild stocks will be affected by escapees are:

1. The extent to which the stock have been selectively bred.
2. The rate of escape or release.
3. Fish harvest size in relation to reproductive maturity and the ability of gametes to survive and develop in the wild.
4. The ability of escapees to survive and reproduce in the wild, as determined by their ability to feed successfully and interbreed with wild stocks.
5. The state (size, distribution, health) of the wild population.

Some of these factors, especially the first two (and in some instances the third) can be influenced by farm management practices. For example it is possible to virtually eliminate the genetic risks to wild populations by using offspring from wild-sourced brood stock, as they will be genetically indistinguishable from wild fish, as long as appropriate spawning regimes are used in the hatchery to maintain genetic diversity in the offspring. Risks can also be minimised by using a robust, well maintained containment system and by controlling breeding in the stock (e.g., Habicht et al. 1994). Issues regarding the genetic contribution from farms to wild population via gametes from farm fish will only apply if the farmed fish achieve reproductively mature size before reaching harvest size and if the gametes are viable in the wild (Dempster and Sanchez-Jerez 2007).

In relation to factors 4 and 5 above, genetic effects are almost certainly species- and location-specific, as they will vary according to the abundance, distribution and behaviour of wild stocks. Genetic issues have also been a particular concern for the salmon and trout industry in the northern hemisphere because there has been a high level of selective breeding, mass releases (hence considerable escape 'pressure'), and successful survival and reproduction of farm progeny in the wild. Simultaneously, the wild population has been over-fished. By contrast, species having healthy wild populations and weak geographic structuring, for example, are likely to be less prone to effects (Cross 2000; Youngson et al. 2001).

4.7.3 Diseases and parasites

There are many known diseases and parasites associated with finfish (see Blaylock and Whelan 2004), and the spread of parasites, viruses and bacterial infections between caged and wild fish populations (from wild to farmed, or vice versa) is a significant concern for the fish farming industry worldwide (Pearson and Black 2001). Diseases and parasites can detrimentally affect stock, which can adversely affect production (e.g., reduced growth rates, unmarketable fish, and mass mortalities). For example, copepod sea lice infestations have hampered development of the salmon farming industry in Europe (particularly Scotland), North America, and Far East Asia (Butler 2002; Nagasawa 2004). These parasites have become more numerous in some locations following the development of marine salmon aquaculture, but the initial infections in Scotland came from wild fish passing through the farms (Rae 2002). The transfer of fish disease can also occur indirectly via contaminated food. In one example, pilchards in Australia were infected by a herpes virus from imported frozen fish food that was fed to caged tuna (Ward et al. 2001).

Despite there being several reported diseases in three species of New Zealand resident salmon, *Oncorhynchus* spp. (Diggles et al. 2002), salmon aquaculture in New Zealand has been largely free from problems with diseases or parasites (M. Gillard, NZKS, pers. comm.). However, this may not be the case for other finfish species proposed for aquaculture in New Zealand. In relation to kingfish, for example, a study of the prevalence and intensity of metazoan ectoparasites on the skin and gills of wild stocks identified two monogenean and four copepod species (Sharp et al. 2003). Four species of disease-causing nematodes have also been recorded from wild kingfish (Diggles 2004). The two most problematic parasites of cultured kingfish in New Zealand have been the monogenean flukes *Benedenia seriolae* and *Zeuxapta seriolae*, which parasitise the skin and gills, respectively. These flukes are introduced to farmed fish from wild populations where they occur naturally, and are likely to necessitate periodic therapeutant treatments (see Section 4.8).

The disease risks arising from finfish culture in shellfish culture regions also need to be considered, as close proximity of finfish and shellfish farms may provide opportunities for some parasites to complete their life cycles. Two parasites that have fish and mollusc hosts in New Zealand are described by Haswell (1903). One digenean trematode *Tergestia agnostomi* uses the Greenshell mussel (*Perna canaliculus*) as intermediate host and the yellow eyed mullet (*Agnostomus forsteri)* as the final host. The other also has the Greenshell mussel as one of its intermediate hosts, and is almost certain to have a finfish final host (S. Webb, Cawthron, pers. comm.). Until the specificity and virulence of parasites such as these is ascertained, the potential for increased prevalence in relation to finfish aquaculture cannot be excluded.

4.7.4 Implications for future finfish farm development in New Zealand

The potential for escapee stock from finfish farms to influence local ecosystems, genetically alter wild stocks, and promote the transmission of pathogens will need to be assessed on a species- and location-specific basis. Such an assessment must consider available knowledge about the proposed culture stock in relation to both genetics and disease issues, knowledge of the receiving environment (e.g., receiving environment values, the extent of wild finfish populations), and opportunities for mitigation of any adverse effects (see next section). In relation to parasites, for example, risks arising from finfish aquaculture at any site could be assessed either practically or by literature review, referring to existing parasitological works such as Diggles et al. (2002), Hine et al. (2000), Haswell (1903), Hickmann (1978), Jones (1975) and Manter (1954), among others. For any significant risks, opportunities for management (e.g., application of therapeutants to reduce the incidence of disease) could then be considered. Similarly, ecosystem effects from escapee fish could be assessed based on a knowledge of ecological and fishery values at proposed farm locations (which is invariably gathered as part of the permitting process) in relation to the nature (e.g., finfish species) and scale of the proposed farm development.

By contrast, it is more difficult to gauge the significance of the genetic issue because so little is known about potential effects that are directly relevant to the aquaculture of true marine species. Whereas the issue appears likely to be relatively insignificant for species such as kingfish that have a wide geographic range and are likely to be bred from wild-sourced brood-stock, case-by-case evaluations in relation to other finfish species may highlight uncertainty about potential effects. In this context, an important consideration will be whether management strategies can be implemented to minimise the likelihood of adverse effects, for example measures to reduce the amount of escapees (see next section).

Finally, it is useful to place the above issues in the wider context of other activities, and recognise that the human-mediated transfer of numerous marine organisms to New Zealand and around the coastline is an ongoing issue. Historically, this reflects deliberate transplants of marine organisms (including salmon), and more recently the inadvertent transfer of a range of native and non-indigenous marine species (including fish), especially via vessel movements and associated mechanisms such as ballast water, fouling and sea chests (e.g., Hayward 1997; Cranfield et al. 1998; Coutts et al. 2003). The alteration to marine ecosystems and transfer of fish diseases via these unmanaged mechanisms is well recognised (Ruiz et al. 2000; Hilliard 2004), hence any incremental risk from finfish culture should be considered within this broader context.

4.7.5 Mitigation and management

The primary means of managing ecological risks from escapee fish is for the industry to adhere to best management practices, for example by having procedures in place (e.g., regular maintenance of nets and structures) to minimise the risk of fish escapes (prevention is virtually impossible). In the case of disease, where risks can potentially arise irrespective of fish escape (e.g., where wild fish pass through a farm) the use of therapeutants may be required, as described in the next section.

4.8. Therapeutants and other chemicals

4.8.1 Overview of issues

Therapeutants (pharmaceutical products, or 'medicines'), anti-fouling paints, and feed are all potential sources of chemicals to the marine environment from finfish farms. Some chemical contaminants have the potential to accumulate and persist in the marine environment, resulting in deleterious effects to biota (Hansen and Lunestad 1992). Recent overseas studies have also highlighted the potential for bioaccumulation of chemicals (e.g., dioxins, PCBs, etc.) in farmed fish (Kiviranta et al. 2000). Some chemical contaminants have been well studied overseas, particularly in regions where extensive use of chemical agents is required to maintain healthy stock (e.g., therapeutants for sea lice control). In New Zealand, issues surrounding the use of chemical compounds at finfish sites have received little scientific attention. This is largely due to the relatively small scale of finfish farming, and the minimal use of chemicals to maintain healthy stock. However, as finfish farming in New Zealand expands into new species and growing regions, the use of chemicals, in particular therapeutants, may increase. The following section provides an overview of the existing sources and use of chemicals at finfish sites in New Zealand, as well the potential ecological effects of therapeutants that may be used for new species.

4.8.2 Feed supplements

New Zealand salmon and kingfish farms use a standard feed that does not contain antibiotics, vaccines, steroids or other growth enhancers. The feed does contain zinc (concentrations of ~130 - 150 mg/kg), which is an essential micronutrient for the prevention of cataract formation and other health problems (M. Gillard, New Zealand King Salmon, pers. comm.). Zinc can be toxic at high concentrations, and can accumulate in sediments beneath fish farms. An assessment beneath salmon farms in the Marlborough Sounds in 2005 found that zinc levels (~ 420 - 560 mg/kg) exceeded the ANZECC (2000) sediment quality guideline for 'probable' ecological effects (410 mg/kg) at sites with low flushing (Hopkins et al. 2006). It has also been found at environmentally significant levels beneath salmon farms elsewhere in New Zealand (Morrisey et al. 2000) and overseas (Solberg et al. 2002; Brooks et al. 2003). The fate and effect of zinc within sediments is currently unknown, however it is likely to bind to sulphide and organic material, which will reduce its biological availability (hence toxicity) while the farm is operational. Nonetheless, high concentrations may hinder long-term infaunal recolonisation rates, for example if a site is fallowed (Morrisey et al. 2000). Feed companies are presently investigating ways of minimising zinc discharges to the seabed, primarily by reducing the content in the feed.

4.8.3 Therapeutants

Therapeutant treatments are typically parasite or disease-specific, as many parasites and diseases are location and host-specific. As such, the potential for environmental issues from therapeutant use will need to be assessed on a case-by-case basis. Presently in New Zealand the salmon industry has not needed to use therapeutants, but with the expansion of finfish aquaculture into new species and growing regions, such chemicals are likely to be necessary. For example, kingfish (*Seriola* spp.) aquaculture is showing considerable promise in New Zealand, and cage-rearing is presently being trialled in the Marlborough Sounds. Early indications suggest that there will be a need for some disease treatments, because kingfish appear to be susceptible to infection by monogenean parasites, as described in Section 4.7 (note that treatments to maintain a healthy fish stock are required by the Animal Welfare Act). In the case of kingfish, parasites can be managed with low concentration in-water baths of praziquantel or hydrogen peroxide (Appendix 2; Sharp et al. 2004a; Mansell et al. 2005). Most therapeutants have limited environmental ramifications as they are usually highly water soluble, break down readily and do not bind to sediments (e.g., formaldehyde; WHO 2002). However, some are administered as feed additives, hence can be deposited on to the seabed. Feeds that contain antibacterial agents for example, can have significant deleterious effects on seabed microbial communities (Hansen and Lunestad 1992).

4.8.4 Antifoulants

Copper-based antifoulant paints are used on most finfish farms to combat biofouling of structures, in combination with mechanical de-fouling methods. In the Marlborough Sounds, New Zealand King Salmon use copper-based paints on external predator nets only, as manual de-fouling is not feasible. Heavy fouling of these nets can impede water flow through the cages, potentially leading to reduced flushing and localised depletion in dissolved oxygen (Braithwaite et al. 2007). Excessive fouling also adds considerable mass and drag to cages, placing additional strain on mooring lines and anchoring systems, and can affect the buoyancy and hence safety of farm structures (M. Gillard, New Zealand King Salmon, pers. comm.). Ablative antifouling paints (including copper-based formulations) slough off over time and can accumulate in sediments beneath finfish farms. Recent assessments at salmon farming sites in the Marlborough Sounds (Hopkins et al. 2006a, b, c) revealed locally elevated copper levels (~70 - 265 mg/kg), which exceeded ANZECC (2000) sediment quality guideline for ‘possible’ ecological effects (65 mg/kg) but not ‘probable’ ecological effects (270 mg/kg). Hence, by comparison with ANZECC (2000) guidelines, copper levels were less elevated than was described above for zinc. Furthermore, in a manner similar to that described for zinc, the ecological implications of elevated copper concentrations are likely to be reduced by low biological availability.

4.8.5 Persistent toxicants

A number of chemical contaminants can persist for many years in the environment and can accumulate in animal tissue. Some compounds, such as mercury, dioxins and polychlorinated biphenyls (PCBs) can also biomagnify (i.e., become more concentrated) across successive trophic levels in the food chain (Connell 1988; Fisher 1995; Braga et al. 2000). These compounds, along with many others, are globally ubiquitous contaminants that accumulate in the tissues of higher trophic level animals, including wild mammals, farm animals and humans, primarily via ingestion pathways (e.g., Päpke and Fürst 2003). Not surprisingly, therefore, overseas studies have reported dioxins, PCBs and a range of other compounds in the tissue of farmed finfish (Serrano et al. 2003; Brambilla et al. 2007), with some contaminants more elevated in farmed fish than wild stocks (e.g., Easton et al. 2002). Such contaminants enter the farmed fish via the raw materials (fishmeal) that are used in feed products, which have accumulated the compounds from lower trophic levels in the ecosystem.

In New Zealand PCBs and/or dioxins have similarly been detected in farmed salmon from the Marlborough Sounds and Big Glory Bay, but at trace concentrations that are well within guidelines for human consumption (Brassett 2003; M. Gillard, NZKS, pers. comm.). Awareness of contaminant issues within the industry and among feed suppliers has led to considerable effort to reduce the fishmeal content of the feed, and replace it with alternatives (e.g., vegetable products), in order to reduce PCB and dioxin concentrations (Bell et al. 2005; Berntssen et al. 2005). Efforts to reduce the use of fish-derived products are evident in a decline in feed conversion ratios from values of over 2 in the early 1980's to approximately 1 in recent times (B. Wyebourne, Skretting Australia, pers. comm.). Furthermore, feed companies that supply the New Zealand industry are increasingly sourcing fish-derived feed products from regions where trace contaminants in raw materials are relatively low, with rigorous testing and certification procedures implemented to ensure this is the case (M. Gillard, New Zealand King Salmon, pers. comm.).

Whereas the focus of the above discussion has been on contaminants in fish tissue, the input of persistent contaminants from finfish farming into the wider ecosystem is also of relevance, but is largely unquantified. One recent overseas study indicates that mercury can be locally elevated in the vicinity of fish farms, potentially leading to biomagnification through the food chain (Debruyn et al. 2006). This is thought to reflect trace levels of mercury in uneaten feed and natural sediment, which becomes mobilised into a biologically available form in the anoxic sediments beneath fish cages. The extent to which mercury or other persistent compounds are elevated in the New Zealand environment due to fish farm activities is unknown. While locally elevated concentrations may be possible, we consider it unlikely that such compounds would be present at environmentally significant levels. There are two main threads of evidence that point to this conclusion.

The first is that concentrations of persistent contaminants in food are at ultra-trace levels (e.g., Easton et al. 2002). To provide some context, zinc in feed is present at around 150 mg/kg (i.e., 150,000 parts per billion), and accumulates in sediments directly beneath cages to around a few hundred mg/kg. By contrast, PCBs and other persistent organic compounds are present in feed at concentrations of tens of parts per billion or less (Easton et al. 2002), which is four orders of magnitude less than zinc (i.e., 10,000 times lower). Furthermore, most persistent contaminants, and certainly persistent organic contaminants like PCBs and dioxins, are highly lipophillic (i.e., have a strong affinity for fatty tissue) and have a very low water solubility (Fisher 1995). As such, the most direct pathway for their uptake is into salmon flesh via ingestion of trace levels in feed. The fact that levels of these compounds in New Zealand salmon are very low provides an indication that significant environmental contamination is unlikely. Note that this is not the same as saying that these contaminants will not be locally elevated by finfish farms, because it is conceivable that they will be to a limited extent. The key point is that they are likely to be present at concentrations that are of minor environmental concern. Furthermore, any environmental contamination that does occur as a result of finfish farming is likely to be small by comparison with other points sources around the New Zealand coastline. Trace metals and persistent organic contaminants (e.g., PCBs, organochlorine pesticides) are present at environmentally significant concentrations throughout New Zealand in coastal areas, especially in urban and port environments (e.g., Roberts and Forrest 1999).

4.8.6 Mitigation and management

There are a number of potential sources of chemical contaminants that could result from finfish aquaculture. In New Zealand, it is evident that salmon farming companies make efforts to minimise contaminant inputs in a variety of ways:

- The use of copper antifoulant paints is minimised to structures where it is essential, and manual defouling used on other structures.
- Together with feed supply companies, the New Zealand industry is progressively reducing levels of nutritional therapeutants in feed (e.g., zinc).
- The industry and feed supply companies are aiming to reduce trace contaminants (e.g., PCBs and dioxins) in feed by replacing fish products with alternatives, and sourcing raw fish products from regions where contaminants are relatively low.

It is important that similar measures are encouraged as part of 'best management practice' with the further development of the finfish farming industry, especially where new companies and new species are involved. Therapeutant use has not been necessary in the New Zealand industry to date, but is likely to be necessary in the future for the culture of kingfish and possibly other candidate species. The use of therapeutants and other chemical treatment techniques for future finfish developments in New Zealand should ideally be based on internationally-accepted standards, and include products that have been approved for use in aquaculture overseas by regulatory agencies such as the United States Food and Drug Administration.

4.9. Waves and currents

4.9.1 Current and wave interactions with finfish farms

Currents and waves play an important role in ecosystem function. In relation to finfish farming these include flushing of food, wastes and nutrients into and out of the localised environment, facilitating mixing processes, and regulating seabed habitats and associated biota through sediment movement. If, for example, currents are not above a critical threshold to allow resuspension of seabed sediments and associated detrital material from a fish farm, this will lead to excessive accumulation with localised enrichment and the development of anoxic conditions (see Section 3.1).

Currents are affected by marine farms due to drag forces that are created by the interaction of a moving fluid on an anchored submarine structure. The mechanism for this interaction has been well studied for a range of engineering applications (e.g., bridge supports in estuaries and rivers), but little research has been conducted in relation to marine farms. In fact, our review of this field yielded literature only for scallop cages in China (Grant and Bacher 2001), mussel rafts in South Africa (Boyd and Heasman 1998) and long-line mussel farm structures in New Zealand (Plew et al. 2005, Morrisey et al. 2006b). These other types of marine farms are sufficiently similar to fish farm structures that the findings can be used to provide some insight into the ways that fish farms might affect currents and waves.

4.9.2 Currents

Water flows will be deflected around and below a fish farm structure as well as passing through it. The extent of which flows are modified is governed by the 'porosity' of the structures. The mechanisms by which marine structures can affect currents are relatively complex and are not discussed here. For present purposes it is sufficient to recognise that there have been two main approaches to assessing effects: (i) measure and compare the differences in currents within and outside of existing farms (Boyd and Heasman 1998; Plew 2005), and (ii) estimate macro-scale changes using hydrodynamic modelling techniques (Grant and Bacher 2001).

The direct method of measuring the change in currents is a useful way of assessing actual effects at existing farm locations. Pioneering work by Boyd and Heasman (1998) on mussel rafts in South Africa showed decreases in current speeds within farms to be as little as 10% of the ambient flow. This study also investigated how changes in structural density (hence changes in porosity) affected currents within farms, revealing that increased rope density led to decreased current velocities. A more recent New Zealand study by Plew et al. (2005) investigated changes in currents at a longline mussel farm, indicating a 38% decrease in current speed and a reorientation of water flow parallel to the alignment of the mussel lines at peak velocities. Unfortunately, neither of these studies successfully described current deflections in detail, and so do not completely quantify the effect of marine farm structures on currents. Also, as each marine farm environment will differ, care needs to be taken in extrapolating such results to other areas and farm designs.

An alternative technique utilising hydrodynamic models described by Grant and Bacher (2001) and used by Morrisey et al. (2006b) in a Golden Bay/Tasman Bay study, involves setting up and calibrating a model without structures, and then artificially introducing them through the use of an increased bed-stress coefficient. This enables the effect of farm structures on currents to be included in the model, including deflection around (but not under) the structure. The results of these techniques applied to an intensively farmed open embayment in China, suggested a 54% reduction in current speeds inside the farmed areas and a 20% reduction within adjacent navigation channels (Grant and Bacher 2001). The authors then studied how these changes in currents would affect flushing, and found associated increases in flushing times (i.e., reduced flushing efficiencies) for this intensively farmed bay. The New Zealand study on a less intensively farmed area showed local changes in currents in the range of -10%

around the majority of the farmed area to +20% in areas where current was deflected close to shore (Morrisey et al. 2006b). The modelling technique has limitations that are beyond the scope of our report to discuss. However, as long as hydrodynamic models are available or can be constructed, this approach provides the only present means of estimating the effects of fish farm structures on water currents in areas where no farms exist.

4.9.3 Waves

Currents generated by short period or swell waves can play a critical role in areas where barotropic (tidal) current conditions are too weak to provide adequate flushing. Episodic wave events in these situations may be critically important in facilitating resuspension and other mitigating processes (Panchang et al. 1997). The currents generated by a wave passing through a marine structure will interact with the structure in the same way as any other current; consequently a loss of energy will be seen as these interactions occur.

The depth at which currents are generated by a wave will depend on wavelength and period. Whether a given site will produce waves of sufficient magnitude and period to interact with the bottom will depend on site depth and wave climate, and the extent to which the wave climate is altered by farm structures. Long period/wavelength waves will produce currents deeper than short period waves. As a result, structures located close to the surface will attenuate energy from the short period waves more than long period waves. Evidence for this phenomenon is provided by Plew et al. (2005) where a mean energy attenuation of up to ~10 % across a mussel farm structure was determined for short period waves (1 - 10 second). In relation to finfish farm site selection and mitigation of effects, minimising impacts on waves would require locating structures in areas of long period wave action, e.g., wave-exposed coastal areas. However, despite benefits for finfish farmers and the environment of moving farms to such areas, significant engineering, cost and servicing constraints would need to be overcome.

4.9.4 Effects to waves and currents from finfish farm developments

Knowledge of the effect of aquaculture structures on currents and waves is limited. Attenuation of waves and currents will depend on the type of structure, its location, and the intensity of farming. Internationally, where aquaculture is intensive by comparison with New Zealand, studies show that ecosystem function may be significantly affected by changes to currents and waves in coastal areas as development increases beyond critical levels (Grant and Bacher 2001). It should also be noted that some functions, such as seabed sediment movement, can be highly non-linear in their response around critical near-bed current values (e.g., Bridge and Dominic 1984; Dade 1993). Consequently small incremental changes at critical current speeds near the seabed can lead to large changes in transport and associated changes within an ecosystem.

In New Zealand, despite evidence for local modification of currents and waves by farm structures, coastal ribbon development of marine farms (as has largely occurred to date) is unlikely to significantly affect bay-wide hydrodynamic characteristics (Plew et al. 2005). While alteration of the wave climate shoreward of farms could theoretically affect ecologically important intertidal and shallow subtidal habitats, our observations at salmon farm sites in the Marlborough Sounds provide no indication that this is an issue at present levels of development.

Even in the absence of bay-wide effects in New Zealand, at the local farm-scale, effects on waves and currents have potential implications for the sustainability of individual finfish ventures, given that reduced flushing can lead to pronounced seabed and water column impacts as explained in Sections 3.1 and 3.2. In fact, a review of the history of finfish farming in New Zealand (Appendix 1) shows that farms have been unsustainable in low energy sites. Experience has shown that these adverse local-scale effects can be minimised by appropriate placement of finfish farms in higher energy areas with relatively high current velocities and/or episodic wave events.

4.10. Carrying capacity and environmental sustainability

4.10.1 Background

The development of aquaculture in New Zealand has been accompanied by concerns and questions over what level of production is environmentally sustainable, i.e., the 'carrying capacity' of the environment for aquaculture. Several different definitions of aquaculture carrying capacity have been described in scientific literature that emphasise maximising production (Carver and Mallet 1990; Bacher et al. 1998). Inglis et al. (2000) take a more holistic approach in relation to mussel aquaculture, by splitting carrying capacity into four definitions, which we have modified as follows:

- Physical carrying capacity: the total area of marine farms that can be accommodated in the available physical space.
- Ecological carrying capacity: the stocking or farm density beyond which ecological effects are unacceptable.
- Production carrying capacity: the stocking density at which harvests are maximised.
- Social carrying capacity: the level of farm development beyond which social effects are unacceptable.

Below we focus on ecological carrying capacity, although we broaden the discussion in Section 4.10.3 to also consider the other definitions.

4.10.2 Ecological carrying capacity

Determination of ecological carrying capacity is difficult because there is no strong foundation for defining limits within a marine ecosystem based on ecological considerations alone. Finfish farming has a range of ecological effects, but whether they are 'significant' is ultimately a value judgement around what is an acceptable level of impact or change, as it will often be difficult to determine finite limits that reflect ecological carrying capacity. For example, seabed ecological effects can be constrained by placing limits on the maximum magnitude or spatial extent of impact that is permitted beneath a fish farm based on certain indicators of environmental change (see Section 3.3.4). These types of limits are typically based on stakeholder perception rather than what an embayment or region can sustain without degradation of the wider ecosystem.

Within the shellfish aquaculture industry the concept of carrying capacity is reasonably familiar, but is often driven by considerations of production rather than environmental effects (e.g., Bacher et. al 1998; Hayden et al. 2000; Gibbs et al. 2002; Duarte et al. 2003). However, broad-scale effects have been evaluated in New Zealand for mussel farms in Pelorus Sound (Ross et al. 1999; Inglis et al. 2000) and in the Bay of Plenty (Longdill et al. 2006), where biophysical models have been used to estimate changes to the flushing, nutrient and production regimes due to present and future developments. Although modelling studies have been undertaken for salmon farms in New Zealand to estimate local seabed and water column effects, few studies have looked at the broader scale question of ecological carrying capacity. This lack of information may in part reflect the small scale of the industry in New Zealand, hence the expectation that present levels of production are well within ecological carrying capacity.

In the few examples from New Zealand (Rutherford et al. 1988) and overseas (e.g., Read and Fernandes 2003) where carrying capacity has been considered, the primary focus has been on nutrient enrichment and eutrophication. Internationally, this has involved determining whether eutrophication may arise based on nutrient models (e.g., Hall et al. 1992; Papatryphon et al. 2005) and based on flushing rates from hydrodynamic models (Lee et al. 2003). For New Zealand, the only similar study was undertaken in relation to salmon farming in Big Glory Bay (Rutherford et al. 1988), where altered nutrient loadings through salmon farming, and a consideration of flushing rates for the bay, were used to estimate algal production. The report concluded that eutrophic conditions were unlikely unless farm production exceeded approximately 5000 tonnes/yr. By comparison, present production levels in Big Glory Bay are around 2000 tonnes/yr (Appendix 1) and have been up to 2800 tonnes/yr (T. Culley, Sanford Ltd, pers. comm.). Interestingly, a phytoplankton bloom occurred following the publication of the Rutherford et al. (1988) report, at a time when production was 1200 tonnes/yr. The bloom event was attributed to natural regional-scale processes rather than a salmon farming effect (Mackenzie 1991).

Subsequent to the work in Big Glory Bay, other modelling approaches have been developed internationally to consider the issue of eutrophication in the marine environment from anthropogenic nutrient enrichment (e.g., Anderson and Pondaven 2003; Baird et al. 2003; Hood et al. 2003; Schartau and Oschlies 2003; Baird and Suthers 2007). Similarly, there is ongoing development and application of models that can potentially be adapted to consider the broader ecosystem effects of finfish farms, including food web models such as ECOPATH, which was recently applied in relation to aquaculture development in Tasman Bay in New Zealand (Jiang and Gibbs 2005).

4.10.3 A wider perspective on carrying capacity

In addition to ecological considerations, carrying capacity can be evaluated in terms of the other definitions in Section 4.10.1. The discussion below considers production and social carrying capacity, assuming that physical carrying capacity is determined as part of the site selection process.

The clearest indicator of production carrying capacity is the health of the farmed fish stock, given that finfish production may become limited because fish-feeding and the associated excretion or loss of waste materials affects the environmental properties of a farmed area (e.g., Butler 2002; Yokoyama 2003). For example, fish respiration can reduce dissolve oxygen concentrations in the water column, and produce toxic excretory products such as ammonia (see Section 3.2). Salmon are particularly sensitive to these types of effects, and many water quality criteria for the protection of aquatic ecosystems are based on guidelines designed to meet the needs of salmonid fish (e.g., ANZECC 2000). In this respect salmon stock can be regarded as the 'canary' for any significant environmental degradation, hence the health of a fish farm stock could, to some extent, be regarded as indicative of the health of the wider ecosystem; i.e., in some instances production carrying capacity could be considered synonymous with ecological carrying capacity.

Using the production approach, carrying capacity at a particular location will be exceeded where water quality degradation has an adverse effect on the stock (such as increased susceptibility of the fish stock to disease, or stock deaths). These extreme responses determine production carrying capacity in some countries (Grant et al. 1998; Pitcher and Calder 1998; Hecht and Heasman 1999; Nunes et al. 2003), such that the development of the industry is self-limiting. 'Self-pollution' at finfish farms has occurred historically in New Zealand as a result of inadequate flushing (Appendix 1), but farm site selection and management have now minimised this risk.

Based on the more recent development of the aquaculture industry in New Zealand, it is likely that future finfish industry development will be constrained by stakeholder views on 'acceptability', to levels that are well within what the natural environment can sustain, that is, social carrying capacity. For example, constraints may include concepts such as zones of acceptable seabed effects, as described for salmon farming in New Zealand in Section 3.3.4. Such limits can be dynamic and may be changed through various processes (e.g., lobbying, social or economic justification). Constraints may also differ based on the relative values (actual or perceived) of different areas. For example, if an aquaculture area is considered to have low social, ecological or other values, then higher limits may be justified, but a popular tourist or ecologically important area may have higher values and hence would require more stringent limits.

These trade-offs are frequently dealt with during the regulatory process to establish a new aquaculture site, where site-specific values and predicted effects primarily determine whether a permit for a potential site is granted, and the extent to which restrictions are placed on development. For example, it is common for proposed site boundaries to be modified to avoid adverse effects on seabed values (e.g., Forrest 1995; Hopkins et al. 2006e; Keeley et al. 2006) and negotiated during the consultation process provided under the Resource Management Act. Similarly, development may be required to proceed in a staged or adaptive manner, for example by specifying staged increases in fish stocking density (and associated monitoring of effects) where there is uncertainty regarding effects (Hopkins et al. 2004).

5. SUMMARY AND SYNTHESIS OF FINDINGS

The marine finfish aquaculture industry in New Zealand is small by comparison with many other countries, and based primarily around sea-cage farming of King salmon (*Oncorhynchus tshawytscha*) at sites in the Marlborough Sounds, Big Glory Bay (Stewart Island) and Akaroa Harbour. There has been recent interest in expansion of the finfish industry to new areas and new species such as yellowtail kingfish and groper, among others. A trial kingfish farm is already established in the Marlborough Sounds. This report reviews existing information on the ecological effects of finfish farming, providing background knowledge relevant to future development. The key points and conclusions from our review are summarised in Section 5.1, and in Section 5.2 we discuss the relative ecological significance of the key issues.

5.1. Summary of ecological issues and mitigation options

5.1.1 Seabed and water column effects

The deposition of uneaten feed and faeces can have pronounced effects directly beneath finfish cages, but there is a rapid improvement in environmental conditions with increasing distance from farm structures (over tens or hundreds of metres). Seabed effects are largely reversible, although recovery is likely to take many months or years, depending on water flushing characteristics. Nutrient enrichment in the water column occurs in the vicinity of finfish farms, leading to concerns regarding the potential of farm-derived nutrients to stimulate phytoplankton blooms. Studies in New Zealand and overseas have not linked algal blooms to fish farming activities. Presently, finfish farm development in New Zealand is of a low intensity and appears to be well within the carrying capacity of the environment. For future development, seabed and water column effects can be reduced by locating farms in well-flushed areas, in areas where species and habitats of special value are not present, or where flushing characteristics alter deposition patterns to a point where adverse effects do not occur. A range of other steps to mitigate effects have already been implemented at salmon farms in New Zealand. For example, feed wastage is minimised and stocking densities managed at levels that ensure the environment is maintained in a condition that is considered acceptable by stakeholder consensus.

5.1.2 Habitat creation and related effects

Finfish farms and other artificial structures in marine environments provide a three-dimensional suspended reef habitat for colonisation by fouling organisms and associated biota. The aggregation of wild fish around artificial structures is well recognised, and fish in the vicinity of fish farms may feed on waste feed, thereby attracting larger fish. Several studies have highlighted the possible role played by fouled structures within the ecosystem, such as enhancement of local biodiversity and productivity. The role of aquaculture structures as reservoirs for the establishment of pest organisms (e.g., fouling pests) is also recognised. The development of finfish farming in New Zealand therefore has the potential to create or exacerbate biosecurity risks in relation to the domestic spread of pest organisms, although there are a number of management approaches possible to mitigate adverse effects. Some of these approaches (e.g., codes of practice, treatments for infected structures) have already been implemented by aquaculture companies in New Zealand in response to existing pests.

5.1.3 Effects on seabirds and marine mammals

Potential effects on seabirds and marine mammals (seals, dolphins and whales) relate mainly to habitat modification, entanglement in structures and habitat exclusion. For seabirds a range of potential effects are recognised, but none are well understood. New Zealand fur seals are a problematic predatory species around salmon farms, leading to use of predator exclusion nets around most sea-cages. There are very few documented cases of entanglement of seals and marine mammals in finfish farm predator nets in New Zealand, and appropriate management responses by the industry (e.g., changes to net design, development of protocols for net changing) mean that entanglement is unlikely to be a significant ongoing issue. Another potential effect of aquaculture generally is the location of marine farm structures in critical cetacean (dolphin and whale) habitat. In relation to finfish farming in New Zealand, adverse effects are highly unlikely at present given the small scale of the industry, and could be minimised in the future by appropriate site selection.

5.1.4 Genetic effects and disease transfer

In any finfish aquaculture operation, there is potential for interaction between farmed and wild fish populations. These include: competition for resources with wild fish and related ecosystem effects (e.g., through predation) from escapee fish, alteration of the genetic structure of wild fish populations by escapee fish, and transmission of pathogens (diseases and parasites) from farmed stocks to wild fish populations. While these types of risks have been highlighted in many overseas studies (primarily in relation to salmon farming), they appear to be relatively minor issues for New Zealand at present. For example, effects from escapee salmon are likely to be minimal given the relatively small scale of the industry, and due to limited salmon numbers in the wild (non-indigenous) populations within existing grow-out regions. For species such as kingfish, and other candidate species that may be trialled in New Zealand, significant ecosystem effects from escapees are unlikely. For kingfish, significant genetic influences on wild stocks are unlikely, as this species has a wide geographic range and the industry plans to breed from wild-sourced brood-stock. Genetic risks for other finfish aquaculture species would need to be considered on a case-by-case basis. Disease is not a significant issue within the New Zealand salmon industry, however issues could arise with kingfish or other new finfish species. This situation could lead to the use of therapeutants (i.e., pharmaceutical medicines) to manage disease risks.

5.1.5 Therapeutants and trace contaminants

Most therapeutants have limited environmental significance as they are usually highly water soluble and break down readily. However, some are administered as feed additives, hence can be deposited on to the seabed. Increased levels of trace metals (zinc and copper) can be found in sediments beneath fish cages in New Zealand and overseas. Zinc is a nutritional supplement necessary for maintaining fish health, and copper comes from antifouling paint whose use is necessary to minimise build-up of marine fouling organisms. Both zinc and copper are likely to bind with sediments and organic material, which will naturally mitigate their risk to the environment. Other chemical contaminants such as dioxins, polychlorinated biphenyls (PCBs) and heavy metals like mercury, are globally ubiquitous compounds that accumulate in animal tissue (including humans) via the food chain. In New Zealand PCB and dioxin levels in sea-cage salmon are well within health guidelines stipulated by various regulatory agencies, and are unlikely to be a risk to the wider ecosystem. The New Zealand salmon industry and feed supply companies implement a number of measures to minimise contaminant inputs to the environment. For example, the industry minimises the application of copper-based paint, and uses manual defouling methods on many farm structures. Similarly, feed companies are: investigating the feasibility of reducing zinc levels in feed, sourcing fish products used in feed pellets from regions where contaminants are relatively low and implementing rigorous testing to ensure safe limits are met, and replacing fish products in feed with alternatives, which will likely result in reduced contaminant inputs in the future. With the further development of the finfish farming industry, especially where new companies and new species are involved, it is important that similar mitigation measures are encouraged as part of 'best management practice'.

5.2. Synthesis of findings

Although there will always be a site-specific element to the magnitude and significance of finfish farm effects, the general issues are reasonably well understood, reflecting the considerable research and monitoring that has been conducted in New Zealand and overseas in relation to the salmon industry. With respect to new developments and the farming of new species, there is sufficient literature available to suggest that many effects will be similar to those described for salmon farms. Collectively, this work indicates that effects of finfish farms are often (but not always) highly localised and reversible, and can be managed in various ways to meet environmental quality criteria. Hence, at the present low level of finfish production in New Zealand the wider ecological significance of many of the issues we describe in this report is likely to be minor. Nonetheless, there are some exceptions to these general statements that we have described throughout this report, and summarised below.

One way to assess the relative ecological significance of the various issues that arise with finfish aquaculture, is to evaluate the actual and potential effects of present or future developments in relation to three criteria:

(i) the magnitude of impacts, which includes both the likelihood and consequences of actual or potential effects;

(ii) the spatial extent of impacts from site-specific to regional scales; and

(iii) the duration of impacts in terms of the length of time effects would continue if farming operations were ceased and farm structures removed.

Numeric scales could be formulated for these criteria according to generic risk-based approaches such as those set out in the joint Australian/New Zealand Standard 4360 on Risk

Management (HB 203:2000), and criteria for ranking the level of certainty about effects could also be included. An example of a qualitative scoring approach that could be used to assess the relative significance of the key ecological effects of finfish aquaculture is shown in Table 3.

Table 3 Examples of criteria that could be used to rank relative ecological significance and uncertainty in relation to the key effects of finfish aquaculture. In this example, likelihood is based on weightings shown (i.e., 0.2 - 1.0) rather than a 1 - 5 score.

Score	1	2	3	4	5
Knowledge and certainty	Based on perception only	Perception and related information from similar activities	Limited information on effects of activity	General effects of activity known	Specific effects of activity well known
Likelihood	Rare (0.2)	Unlikely (0.4)	Moderate/possible (0.6)	Likely/probable (0.8)	Almost certain (1.0)
Consequences	Negligible	Minor	Moderate	Major	Catastrophic
Spatial extent (from site)	Site-specific (< 500m)	Local area (500m - 5 km)	Regional (> 5 km)	NA	NA
Duration	Short-term (< 1yr)	Medium-term (1 - 5 yrs)	Long-term (> 5 yrs)	NA	NA

Based on these scores a numeric relative ranking for the overall ecological significance of each issue could be calculated as *magnitude (i.e., likelihood x consequences) x spatial extent x duration*. This would provide an indication of the *relative* ecological significance of effects. Note that *actual* significance will depend on many site-specific factors such as the intensity of farming in a given area, the sensitivity and values of the receiving environment, and the extent to which mitigation is effective. This type of risk-based evaluation should be undertaken via a consensus process involving a wide group of experts and stakeholders. It was beyond the scope of this project to undertake such as assessment, but the criteria for assessing ecological significance can nonetheless facilitate a general understanding of the relative importance of the various issues discussed in this report, and also provide a sense of how relative importance might change in the event that the industry expands or diversifies into new species.

When considered against the above criteria, biosecurity issues relating to the spread of pest organisms are likely to be relatively important in relation to present and potential finfish farming in New Zealand. This view is consistent with an aquaculture risk assessment described by Crawford (2003) for Tasmania. Although the magnitude of pest effects (e.g., per unit area) is likely to be less than in the case of seabed impacts, by comparison with all other ecological stressors the spread of pest organisms by finfish farming activities can occur at regional scales, and potentially lead to irreversible changes to coastal ecosystems (Elliot 2003). Even though the likelihood of such risks can be reduced by management, risk avoidance is often not possible. However, whether the spread of a given pest organism by finfish farming activities (e.g., via inter-regional transfers of infected equipment) is a significant risk depends on a number of different factors, as discussed in this report.

Seabed enrichment effects from the deposition of faeces and uneaten feed are also likely to emerge as a relatively significant issue when assessed against the criteria in Table 3. Seabed effects beneath finfish farms are typically quite pronounced, and even with best management practices some level of impact is generally unavoidable. However, while the magnitude of effects can be relatively high, effects are also highly localised and are expected to be reversible in the medium to long term. Furthermore, while the ecological significance of seabed impacts may be high in a relative sense, in absolute terms the broader consequences can be mitigated by appropriate site selection, as noted in several places throughout this report.

For issues other than those relating to pest organisms and seabed effects, ecological significance is arguably less, at least at the present level of finfish aquaculture in New Zealand. In some instances this reflects low likelihood events that are presently well-managed, such as adverse effects on marine mammals. Similarly, in the case of disease transfer and genetic alteration of wild stock, the ecological effects of present developments are either minor or can be effectively managed. Changes in ecological risk associated with fish farming, and in the relative importance of the different ecological issues, are likely to result from future developments that involve the aquaculture of new species or a significant increase in the number or size of finfish farms. In relation to new species, interactions between farmed and wild fish stocks, and the associated potential for genetic alteration and disease should be carefully considered, as should the use of chemical therapeutants to manage disease risk. For the other issues discussed in the report, ecological consequences are likely to be similar for most of the candidate species that may be farmed in the future, with effects related primarily to the local intensity and geographic scale of farming (assuming procedures for appropriate site selection and effective management are in place to mitigate any adverse effects). Note, however, that for large-scale new developments, cumulative and threshold effects will also need to be considered. For example, high intensity finfish farming within individual embayments could lead to nutrient enrichment at levels of greater significance (in relation to algal bloom formation) than presently appears to be the case.

Where new developments are proposed it is almost inevitable that some areas of uncertainty will arise for which answers regarding ecological risk are not straightforward. At the farm scale, mitigation of poorly understood risks may rely on industry 'best management practice' or adherence to internationally accepted guidelines, at a level of effort that is reasonable within the context of sources of risk from other activities. In this respect, the New Zealand salmon farming industry already has codes of practice for some of its operations (e.g., Big Glory Bay), or develops them to deal with particular ecological risks as the need arises. In relation to future finfish farming activities, consideration should be given to the development of a more comprehensive environmental code of practice for the industry as a whole. Read and Fernandes (2003) refer to several examples from Europe that would provide useful guidance on the scope and content of such a code. At greater scales of development (i.e., where multiple farms or atypically large farms are proposed) it may be appropriate for finfish farming to proceed in a staged manner within an adaptive management and monitoring framework. Staged development will be of particular importance for issues where the potential for adverse cumulative effects are recognised, but not well understood.

Finally, we note that judgements as to the ecological significance of finfish farming should ideally be made in relation to other sources of environmental risk to coastal systems, so that the effects of finfish aquaculture are placed in context. This holistic approach was recently applied by Cawthron and Environment Waikato for mussel farm development in the Firth of Thames using a Relative Risk Model (Elmetri et al. 2005). In that approach, the relative risks to predefined endpoints (particular species and populations, and habitats) from a number of sources and stressors including agricultural land use, climate change, marine farming, fishing, urban development etc., were investigated. The outcome of the Firth of Thames work was that relative risks were identified to all of the habitats in question from all of the stressors. An important feature of the Relative Risk Model approach is that parameter uncertainty can be explicitly addressed. Such methods can be applied in a defined area (e.g., a harbour) or across multiple regions, and provide a defensible basis for making resource management decisions.

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APPENDIX 1

HISTORY OF SALMON FARMING IN NEW ZEALAND

Appendix 1 History of salmon farming in New Zealand

Due to dwindling supplies of wild fish in the world's oceans, fish farming has been developed and encouraged in many parts of the world. During the 1970's sea cages were used in Norway and Scotland for raising Atlantic salmon, with salmon aquaculture throughout the world growing dramatically since then. Over the last twenty years, for example, production has increased from 150,000 tonnes in 1988 to over 1,700,000 tonnes in 2006. Atlantic salmon represents approximately 80% of this total. In New Zealand King (or Chinook) salmon (*Oncorhynchus tshawytscha*) is the only salmon species farmed, and accounts for approximately half of the worldwide King salmon production (i.e., approx. 7450 tonnes).

The first sea-cage King salmon farms in New Zealand were established in 1982 at Big Glory Bay, Stewart Island. Additional sites were then developed at a number of sites in the Marlborough Sounds. The New Zealand King Salmon Company Ltd was formed in 1996 with the privatisation and merger of New Zealand's two largest salmon companies, Southern Ocean Seafood Ltd and Regal Salmon Ltd. New Zealand King Salmon harvests approximately 5,000 tonnes annually from four farm sites in the Marlborough Sounds and a decision is pending for an additional farm site at Clay Point, Tory Channel.

Sanford Ltd (Sanfords) is the only other major company farming King Salmon in New Zealand. Their operations are based at Big Glory Bay, Stewart Island. Sanfords produce 2,000 tonnes of salmon each year. In the late 1980s and early 1990s, several salmon farms were operational within Big Glory Bay however there is now only one farm operating there within a licensed area of 4.5 ha. Due to a phytoplankton bloom within the bay in the early 1990's a large amount of farmed salmon were lost and a nitrogen model was produced to describe and predict conditions that promote phytoplankton growth. As a result of the model, conditions of the farming licence were amended in 1995 enforcing restriction limits on the amount of food that can be used each year. Within Akaroa Harbour, two salmon farms have been operating since 1984 in Lucas Bay and Titoki Bay with a licence to farm a 1.76 ha and 2.94 ha site, respectively, for King salmon and other species. The farms currently occupy 0.35 ha and production is approximately 200 tonnes of salmon per year.

The rationale for selection of potential sites for salmon farm development in New Zealand has evolved considerably through experience gained during the past 25 years. Prior to 1990, farms were generally established at near-shore, relatively shallow (i.e., < 30 m depth) sites that were poorly flushed due to low average current speeds (i.e., typically < 5 cm s^{-1}). In addition, in the Marlborough Sounds many sites experienced summer temperatures that were near the upper limit of the range appropriate for farming King salmon. Many of the farms that were initially established have therefore been removed, relocated or fallowed due to poor environmental, biological and financial performance (Table A1).

The trend in recent years has been to establish salmon farms in locations with stronger currents, where oceanic water and cooler summer water temperatures prevail (e.g., Tory Channel in Queen Charlotte Sound). A site established in 1990 at Te Pangu Bay, Tory Channel has proven particularly successful and appears sustainable over the long term. The high energy current regime and inflow of cooler Cook Strait water have resulted in good growth rates and fish condition, and reduced seabed impacts. As technology improves, there may be potential in the future for locating farms in offshore open ocean sites where many of the present environmental and production constraints would be relieved.

Table A1 Chronology of salmon farm development in New Zealand since the early 1980's.

Year	Farm	Outcome of farming
1982	Big Glory Bay, Stewart Island	First salmon farm established in New Zealand. The operation grew to several farms, although this has now decreased again to one farm. In an effort to achieve higher winter growth rates, some sites moved to the warmer sea water conditions of the Marlborough Sounds.
1984	Mill Bay, Kenepuru Sound	Poor environmental conditions for salmon resulting in the farm being transferred to Ruakaka Bay. Farm closed in 1986/1987.
1984	Akaroa Harbour	Small scale salmon farm established. Still operational.
1984	Hallam Cove, Marlborough Sounds	Small pilot-scale salmon farm established in relatively shallow (20-24m) water with minimal current flow. Moved in 1990 to better environmental conditions at Waihinau Bay, which evolved to 2-3 sites.
1984	Ruakaka Bay, Marlborough Sounds	First developed close to shore but soon moved further offshore. A relatively low current site which experiences oceanic flushing through the Tory Channel and wave action from ferry traffic. Still operational.
1985	Crail Bay, Marlborough Sounds	A shallow, low flow site which had warm water temperatures and low current flows. Farm was closed in late 1980's.
1987	Port Underwood, East Marlborough	Small sized farm established although only in place until 1991.
1989	Otanerau Bay, Marlborough Sounds	Situated in a low current environment and subjected to warm temperatures during summer months. Still operational.
1989	Waihinau Bay, Marlborough Sounds	Moved further offshore to deeper water in 1991. Water temperatures cooler during summer with better flushing than Hallam Cove due to the influx of oceanic water. Still operational.
1990	Te Pangu Bay, Marlborough Sounds	Located in Tory Channel. Excellent fish health and growth rates attributed to high current flows and cooler oceanic waters. Although currents have challenged moorings in the past, technology has evolved and the latest engineering designs are being used successfully.
1994	Forsyth Bay, Marlborough Sounds	Relatively low current site with a mud substrate below the farm. Fallowed in 2001 and monitored annually to investigate recovery of the seabed.
Early 1990's	Port Ligar, Marlborough Sounds	Low current site with a mud bottom. Discontinued in 1996.
2007	Clay Point, Marlborough Sounds	Recently granted resource consent. Similar site characteristics to Te Pangu (high current flows and cooler water temperatures). Proposed mooring designs considered to be affective to safely moor the farm structure in the strong currents.

APPENDIX 2

TREATMENTS FOR COMMON KINGFISH PARASITES

Appendix 2 Summary of treatments for common kingfish parasites and their potential environmental effects

Treatment	Application	Properties/Environmental fate	Restrictions on use
Hydrogen peroxide H_2O_2 bathing	Has been used effectively in the treatment of monogeneans in Japan for *Seriola* sp. and is a common treatment for the control of both skin and gill flukes in the South Australian kingfish industry because it is effective and presents no food safety issues (Mansell et al. 2005).	Highly soluble in water. Degrades rapidly to water and oxygen. No significant adverse environmental implications	No relevant environmental restrictions found
Fenbendazole ($C_{15}H_{13}N_3O_2S$) Bathing/orally	A broad spectrum antihelminthic which was introduced in the mid nineties for use in fish culture, where it was found to be effective against endo- and ecto-parasites in salmon, cod and rainbow trout (Iosifidou et al. 1997).	Insoluble in water, high stability (http://www.chemicalland21.com/lifescience/ phar/fendendazole.htm) Commonly used in humans, sheep cattle and horses. Limited withdrawal time is needed for fish treated with this method destined for human consumption (Iosifidou et al. 1997).	No relevant environmental restrictions found NZFSA limit of 0.5 mg/kg residual content in animal livers.
Praziquantel ($C_{19}H_{24}N_2O_2$) Bathing or oral	Used to control monogenean diseases in fish by bath treatment (Kim et al. 2003). Also used to treat the skin and gill flukes of farmed kingfish, and infestations of several species of monogenean ectoparasites (Thoney & Hargis Jr 1991; Lee et al. 1998). Highly effective for removing *B. seriolae* from kingfish (Sharp et al. 2004b; Mooney et al. 2006). Treating for a longer duration aids the removal of flukes and allows lower drug concentrations to be used. Single treatments not so effective in reducing the viability of the eggs (Sharp et al. 2004b); so both a primary and secondary treatments are recommended (Sharp et al. 2004a). In Japan, Hadaclean® (active ingredient praziquantel, Bayer Ltd.) is used for the oral treatment of *B. seriolae* infections. In New Zealand 50 mg/kg administered orally for 8 days is effective in eliminating *Z. seriolae* and significantly reducing the intensity of *B. seriolae* infections of kingfish.	Poorly soluble in water, partially solved by new liquid form (Prazipro). Binds strongly to lipids, soils and biodegraded by microflora. (http://www.pfizerah.com /PAHimages/msds_us/EQ.pdf). Part of avermectin family, LCD50 for Rainbow trout 0.000025 g/m^3. Studies have indicated minimal praziquantel accumulation with the body tissues of fish a useable doses (Tubbs & Tingle 2006 & Kim et al. 2003). Using a 24 hour dosing interval, praziquantel appears only likely to accumulate in a very limited manner in the skin or plasma of kingfish, which is believed to be due to the rapid clearance of the drug, either via hepatic metabolism or renal excretion, rather than poor absorption (Tubbs & Tingle 2006).	No relevant environmental restrictions found NZFSA limit of 0.1 mg/kg residual content in flesh.
Formalin (CH_2O) Bathing	A saturated solution comprised 37% formaldehyde by weight, and 6 to 13% methanol in water. Bath treatments are used to control external parasitic infections of fish which include parasites on the gills, skin and fins. Two brands of formalin, Formalin-F and Paracide-F have been approved for use in fish aquaculture by the Food and Drug Administration (Francis-Floyd 1996). The toxicity of formalin increases with increasing water temperature. The concentration of formalin used should be decreased when water temperature exceeds 21°C.	Highly soluble in water and not likely to accumulate in sediments. Breaks down rapidly in air and water, thus does not usually persist in the environment (WHO 2001). Approx. 50 mg/kg of bioavailable formaldehyde is required to inhibit the tactile response of snails (Verschueren 1996). Each 5 g/m^3 of formalin applied removes 1 g/m^3 of dissolved oxygen (Francis-Floyd 1996). If treatment is needed within an enclosed environment, additional aeration of the water is required.	ANZECC (2000) guideline for formaldehyde for the level in water found to cause the tainting of fish flesh or other aquatic organisms is 95 g/m^3.
Fresh water bathing	Freshwater baths effective in treating some salt water parasites.	Highly soluble in salt water.	None