3. ECOLOGICAL EFFECTS OF INTERTIDAL PACIFIC OYSTER CULTIVATION

3.1. Introduction

Intertidal oyster cultivation is one of the most significant aquaculture industries world-wide (FAO 2006). While the global industry is based on a range of species, Pacific oysters (*Crassostrea gigas*) are by far the most dominant, having been spread either deliberately or inadvertently (*e.g.* via shipping) to many countries (Kaiser *et al.* 1998). Pacific oysters are endemic to Japan, and were first observed in New Zealand in Northland in 1971 (Dinamani 1971) and were later observed on the South Island (Jenkins & Meredyth-Young 1979). They may have arrived in New Zealand as early as 1958 (Dromgoole & Foster 1983), possibly following inadvertent introduction via shipping mechanisms such as ballast water discharge or hull fouling. Intertidal cultivation of Pacific oysters began in New Zealand on the tidal flats of Northland harbours in the mid-1970s, in favour of an industry at that time based on cultivation of native rock oysters (*Saccostrea glomerata*).

The total area consented for intertidal Pacific oyster farms in New Zealand now exceeds 1000 ha, but not all of the allocated space is in production. As indicated in Section 1, operational farms number more than 200 and occupy approximately 750 ha of estuarine habitat. Most of the intertidal farms are located in the estuaries of northern New Zealand (Figure 1). Key cultivation areas include Whangaroa, Parengarenga, Mahurangi, and Kaipara Harbours, as well as the Coromandel Peninsula, Ohiwa Harbour and Bay of Islands (MFish 2006). The majority of oyster farms in these areas consist of wooden racks (~50 m L x 1 m W x 0.75 m H) in the lower intertidal zone. Sticks to which juvenile oyster spat are attached are laid across these racks and are therefore elevated above the sediment (Figure 15 & 16). To produce single seed (unattached oysters), the oysters are sometimes stripped from sticks and placed in plastic mesh bags or trays. Racks are spaced several metres apart to allow access by farm barges. The spat supply for the northern industry has historically relied on wild-caught spat, mainly from farms in Kaipara Harbour. Increasingly, however, the industry is using selectively bred single-seed oyster spat from a hatchery in Nelson. Last year approximately 20% of the industry spat supply came from this hatchery source.

Owing to a high global demand for Pacific oysters, there is considerable interest in the further development and expansion of this industry in New Zealand. As part of this development, it appears likely that the industry will slowly convert to intertidal long-line culturing using an Australian-designed "BST system" (Figure 16). This system involves enclosing oysters in cages which are suspended from a plastic-coated wire cable strung between posts. The cables can be adjusted in height to provide more control over the farming process (*e.g.* control of oyster growing height, control of biofouling) compared with rigid rack methods. The BST system also provides a more desirable single seed oyster and enables greater mechanisation of the farming operation (Handley & Jeffs 2002; Hay & Lindsay 2003). Most of the main oyster growing areas now have small areas (a few hectares) where the BST method is used. A new oyster farm recently consented for Kaipara Harbour will cover 76 ha when fully developed, and aims to exclusively use the BST system. There is also increasing interest in the development of subtidal suspended culture methods for Pacific oysters. Subtidal culture is currently undertaken at only a very small scale in New Zealand, or used for oyster fattening (Handley & Jeffs 2002). There are ongoing efforts, however, to develop methods that overcome some of the barriers to successful subtidal culture (*e.g.* excessive fouling), to enable this approach to be more widely used (Hay & Lindsay 2003; Olin Pilcher, Cawthron, pers. comm.).

a. b.

Figure 15. Pacific oyster cultivation areas in northern New Zealand; a. Mahurangi Harbour (R Creese); b. Waikare Inlet (B Howse, Northland Regional Council).

a. b.

Figure 16. Pacific oyster cultivation; a. Elevated intertidal oyster racks in northern New Zealand (B Forrest); b. BST system that encloses oysters within suspended cages (Handley & Jeffs 2002).

3.1.1. Scope of this review and information sources

In Section 3 of this report we restrict our review to discussion of ecological effects from intertidal Pacific oyster cultivation, as this represents the mainstay of the New Zealand industry. Effects arising from the future development of subtidal Pacific oyster culture referred to above, and the culture of other oyster species (*e.g.* the flat oyster *O. chilensis*), are discussed separately in Section 4.3.1

To date there has been only one field study of intertidal oyster culture effects in New Zealand (Forrest 1991). That work focused on ecological effects of Pacific oyster racks on seabed habitats in Mahurangi Harbour, and pertinent information from that work has recently been published (Forrest & Creese 2006). A broader range of potential ecological risks was discussed in relation to a proposed Pacific oyster and mussel farm developments in Kaipara Harbour (Gibbs *et al.* 2005; Hewitt *et al.* 2006) and, more recently, a review paper has been produced that provides a synthesis of ecological risks associated with intertidal oyster aquaculture (Forrest *et al.* 2009). The review in turn was an extension of a brief overview of ecological issues associated with Pacific oyster cultivation in Northland, which was produced for Northland Regional Council as part of the Foundation for Research Science and Technology Envirolink advice scheme (Forrest *et al.* 2007). Additional work on the effects of mudworm infestations on cultured oysters has also been conducted (Handley & Bergquist 1997) but wider ecological ramifications were not considered. Based on these information sources, it is apparent that:

(i) The actual or potential nature and magnitude of effects from oyster farms in New Zealand are similar to that described for comparable forms of intertidal oyster aquaculture in estuaries overseas.

(ii) The broad interactions of oyster farms with the environment, and the magnitude of effects, are similar to other forms of aquaculture, especially mussel farming (Section 2).

In the sections below we provide an overview of the known or potential effects of Pacific oyster farming in New Zealand within the wider context of other relevant knowledge from New Zealand and overseas. The focus is almost exclusively on the sea-growing stage of intertidal oyster aquaculture. Where appropriate we include reference to on-ground cultivation methods (widely practiced in some countries) and natural or restored oyster reefs to provide insight into the potential ecological roles of intertidal oyster cultivation. Some of the information we present is extracted, often verbatim, from the Forrest *et al.* (2008) review or earlier Envirolink report, and some of the generic information is the same as provided for mussel farming in Section 2. The text is modified as appropriate, however, to reflect the New Zealand oyster farming situation and the particular purpose of this report.

While we recognise that a range of short-term ecological effects may arise as a result of oyster farm construction, and in relation to other aspects of farming operations such as spat collection at farming sites, we make the assumption that the site-specific effects of such activities are similar or less than in the case of the cultivation phase. The only exception is in Section 3.5.5, where we recognise the potential role of oyster (including spat) movements in the introduction and spread of pest organisms.

3.2. Overview of Pacific oyster cultivation issues

The occupation of space by intertidal structures means that oyster cultivation can conflict with a range of other environmental, social and economic values (DeFur & Rader 1995; Simenstad & Fresh 1995; Kaiser *et al.* 1998; Read & Fernandes 2003). However, it is the ecological effects of intertidal oyster farming that have received the most scientific attention internationally, with the literature dominated by papers that describe cultivation effects on sediments and associated biota (Ito & Imai 1955; Kususki 1981; Mariojouls & Sornin 1986; Castel *et al.* 1989; Nugues *et al.* 1996; Spencer *et al.* 1997; De Grave *et al.* 1998; Kaiser *et al.* 1998; Forrest & Creese 2006; Dubois *et al.* 2007). In addition to seabed effects, there are a range of broader ecological issues associated with intertidal oyster aquaculture that are less well recognised or need to be considered in a comparative context (Figure 17). These include the introduction of pests and disease, creation of novel habitat, alteration to water flows and nutrient cycles, and depletion of suspended particulate matter (especially phytoplankton) by oyster crops. Related considerations are the wider ecosystem consequences of such changes, for example implications for fish, seabirds and marine mammals.

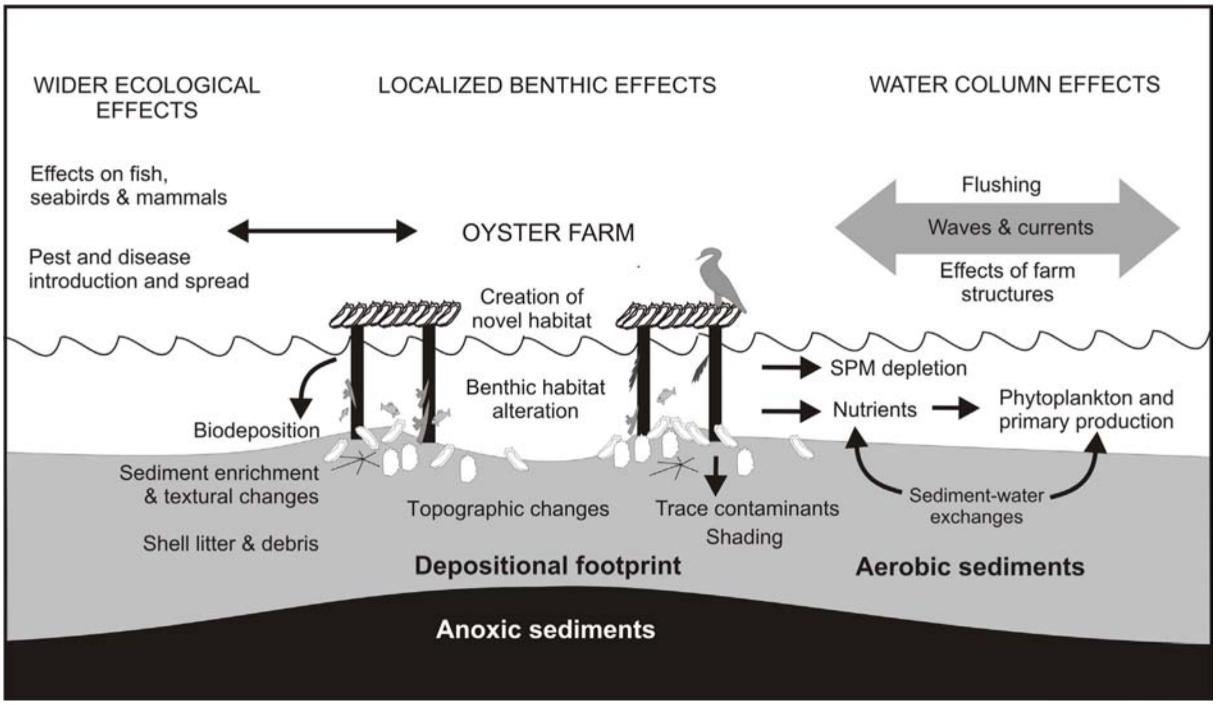

Figure 17. Schematic of actual and potential ecological effects from intertidal oyster cultivation (modified from Forrest *et al.* 2007).

While the broad range of ecological effects from oyster aquaculture have received some attention in the literature, much of the knowledge-base relates to natural oyster reefs or on-ground culture methods (Ruesink *et al.* 2005; Powers *et al.* 2007). Furthermore, where the ecological effects of intertidal methods are specifically addressed, the complexity of some of the ecosystem issues and interactions depicted in Figure 17 means they are often considered or reported superficially (Crawford 2003); alternatively where more thorough assessment is undertaken it is usually for specific issues in isolation. The review by Forrest *et al.* (2009) was a more integrated and in-depth assessment in which the relative significance of each issue was considered within the context of the full range of actual or potential ecological effects.

3.3. Seabed effects

3.3.1. Biodeposition

Nature and magnitude of depositional effects

Oyster farms act as biological filters that remove suspended particulate matter from the water column as it flows through the culture and processes the material into waste products in the form of faeces and pseudofaeces. These waste products (generally referred to as 'biodeposits') are heavier than their constituent particles, and readily settle on the seabed beneath culture areas (Haven & Morales-Alamo 1966; Kusuki 1981; Mitchell 2006). Since biodeposits are organic-rich and consist of a substantial proportion of fine particles (*i.e.* silt and clay), seabed sediments beneath oyster cultures can become organically enriched and fine-textured relative to surrounding areas, and can have a reduced REDOX potential (Forrest & Creese 2006).

Changes in physico-chemical characteristics stemming from an enrichment of organic material beneath oyster cultures can lead to a displacement of large-bodied macrofauna (*e.g.* heart urchins, brittle stars, large bivalves) and the proliferation of small-bodied disturbance-tolerant 'opportunistic' species (*e.g.* capitellid polychaetes and other marine worms). Localised minor-to-moderate enrichment effects of this nature have been described (to varying degrees) beneath intertidal oyster farms in Mahurangi Harbour (Forrest 1991; Forrest & Creese 2006) and in numerous studies overseas (Kususki 1981; Mariojouls & Sornin 1986; Nugues *et al.* 1996; Spencer *et al.* 1997; De Grave *et al.* 1998; Kaiser *et al.* 1998; Forrest & Creese 2006; Dubois *et al.* 2007). Castel *et al.* (1989) also described an increased meiofaunal density and biomass beneath oyster trestles in France.

Without exception, it is apparent that direct biodeposition effects associated with oyster cultivation are highly localised to farmed areas (extending tens of metres or less from structures in Mahurangi Harbour) and greater directly beneath racks than between them (Forrest & Creese 2006). The magnitude of biodeposition effects appears comparable for that described for subtidal mussel culture in New Zealand (Section 2; Kaspar *et al.* 1985) but relatively minor by comparison with that described for some mussel culture areas overseas (Mattsson & Lindén 1983; Grant *et al.* 1998) and the suspended subtidal culture of fish (Brown *et al.* 1987; Karakassis *et al.* 2000; Forrest *et al.* 2007). Extreme enrichment effects in relation to oyster farming have been described only for suspended culture systems in Japan, and had been attributed to repeated culturing and over-stocking (Ito & Imai 1955; Kusuki 1981).

Factors affecting the magnitude and spatial extent of seabed effects

The magnitude of effects from biodeposition will depend primarily on oyster stocking density and biomass in relation to the flushing characteristics of the environment (Pearson & Black 2001). Additionally, the level of biodeposition for a given stocking density, and the assimilative capacity of the environment, may vary seasonally (Kusuki 1981; Souchu *et al.* 2001; Mitchell 2006). To our knowledge, the relative role of these different attributes has not been quantified for oyster farms. As with other forms of aquaculture, the capacity of the environment to assimilate and disperse farm wastes will mainly depend on water current velocity and wave action (Souchu *et al.* 2001), as these factors control the size and concentration of the depositional 'footprint'. Increased flushing from currents and waves will reduce biodeposit accumulation and increase oxygen delivery to the sediments, thus allowing for greater assimilation of farm wastes (Findlay & Watling 1997; Mitchell 2006). Negligible enrichment effects from intertidal oyster farms in Tasmania have been attributed to a combination of low stocking densities and adequate flushing (Crawford 2003; Crawford *et al.* 2003; Mitchell 2006). Similarly, experience with fish farming shows that well-flushed sites have depositional footprints that are less intense (but more widely dispersed) than shallow, poorly flushed sites (Pearson & Black 2001).

3.3.2. Accumulation of shell litter, debris and associated organisms

The accumulation of live oysters, shell litter and farm debris (*e.g.* oyster growing sticks), and fouling or epibenthic organisms beneath growing racks can be the most visible effects of oyster farms during low tide. Oyster shell and debris is evident, for example, at Mahurangi Harbour and Waikare Inlet oyster farms as in Figure 18. The extent of drop-off to the seabed is likely to depend on the type of cultivation system (*e.g.* stick culture is likely to deposit more debris than basket culture) and may be exacerbated periodically during harvesting. The degree of fouling accumulation will depend on the degree to which structures become fouled, and patterns of natural drop-off or active defouling by farm personnel. Subsequent effects to benthic community composition, for example aggregation of carnivorous and deposit feeding species in response to the food supply (*e.g.* sea stars) and competition between deposited shellfish and benthic filter-feeders, are indicated for other forms of bivalve aquaculture (Smith & Shackley 2004; Hartstein & Rowden 2008) and conceivably occur in the case of intertidal oyster culture. Excessive deposition and decay of fouling biomass may also exacerbate the organic enrichment described above, although such effects would likely be patchy beneath cultivation areas.

Hard surfaces such as live and dead oysters, calcareous debris (*e.g.* bivalve shells, serpulid polychaete tubes) and farm materials potentially provide novel habitats for fouling organisms and associated mobile biota, which would otherwise not occur (or be at reduced densities) in the absence of oyster growing. Such effects have been widely documented overseas in the case of on-ground shellfish culture (Dumbauld *et al.* 2001; Hosack *et al.* 2006; Powers *et al.*

2007) and oyster reefs (Peterson *et al.* 2003; Escapa *et al.* 2004; Ruesink *et al.* 2005; Coen *et al.* 2007). For example, the structured habitats provided by oyster reefs can support a diversity of taxa (macroalgae, sessile and mobile invertebrate epifauna, infauna, fish, birds) that may be absent or at reduced densities in adjacent unvegetated soft-sediment habitats (Ruesink *et al.* 2005 and references therein).

Probably the main factors limiting the potential value of fouling habitat in the case of oyster farms would be the effect of enhanced sedimentation beneath rack structures, or sediment resuspension and physical disturbance from farming activities (Forrest & Creese 2006; see below). Accumulated shell, sticks and other inorganic debris from intertidal culture may persist for many years after the cessation of farming; the introduction of novel habitat created by such materials may result in long-term shifts in benthic community composition. There is likely to be site-specific variation in the significance of such effects according to environmental conditions, oyster species and density, and the extent of accumulation. Increasingly, regulatory authorities in other countries are stipulating management practices to mitigate such effects (e.g., requiring removal and land disposal of accumulated material).

Figure 18. Shell litter and sticks from abandoned oyster racks; a. Mahurangi Harbour (B Forrest); b. Waikare Inlet (B Howse, Northland Regional Council).

3.3.3. Changes in seabed topography and sedimentation

Changes in seabed topography (in the order of a few tens of centimetres at maximum) have been described beneath oyster farms in several countries, including New Zealand (Ottmann & Sornin 1982; Everett *et al.* 1995; Forrest & Creese 2006). Such changes can be attributable to the accumulation of shell and inorganic debris, and erosion or accretion of sediment beneath and between farm structures (Forrest and Creese 2006). Sedimentation rates are elevated directly beneath cultures (Mariojouls & Sornin 1986; Sornin *et al.* 1987; Nugues *et al.* 1996) and in Mahurangi Harbour were almost three times greater than at control sites (Forrest & Creese 2006). However, Forrest & Creese (2006) suggested that effects on seabed topography were likely to be more related to changes in hydrodynamic conditions caused by the structures themselves rather than increased sedimentation rates. In New Zealand, sediment build-up to the top of Pacific oyster racks (Figure 19) can occur at sites where rack alignment is perpendicular to tidal currents and results in the entrapment of suspended sediments (Handley & Bergquist 1997). In such instances oyster leases have become un-useable and farming abandoned, with shell litter and debris still evident many years later (see Figure 18). The redistribution of sediments either into (Kirby 1994) or out of (Mallet *et al*. 2009) culture cites may also occur in relation to events such as storms that lead to large scale sediment mobilisation.

Figure 19. Sediment accumulation beneath oyster racks. (Photo: B Forrest).

3.3.4. Physical disturbance

At least two studies have implicated physical disturbance, in particular from vessel movements (*e.g.* propeller wash) and farm personnel walking between cultivation structures, as having a strong influence on benthic changes beneath oyster farm sites (De Grave *et al.* 1998; Forrest & Creese 2006). Forrest & Creese (2006) described an association between benthic macrofaunal composition and decreased sediment shear strength (increased ability for sediments to erode or resuspend) beneath Pacific oyster cultures in Mahurangi Harbour, which they suggested could reflect physical disturbance beneath racks (Figure 20). Physical disturbance is conceivably equally important as biodeposition and accumulation of shell material as a source of impact beneath cultivation areas, and perhaps more important where deposition effects are negligible. The relative importance of these two effects is yet to be rigorously evaluated, in part due to the difficulty of isolating influences of physical disturbance from the effects of biodeposition and subsequent organic enrichment of the seabed.

Figure 20. Oyster farm operations are a source of physical disturbance beneath oyster racks (Photo: B Forrest).

3.3.5. Shading

Shading by farm structures could reduce the amount of light reaching the seafloor, with implications for the growth, productivity, survival and depth distribution of ecologically important primary producers such as benthic microalgae, macroalgae or seagrasses. Overseas studies have found effects on seagrass beneath oyster farms to be negligible (Crawford 2003), although at least one study has described adverse effects on seagrass beneath oyster racks and suggested shading as a possible cause (Everett *et al.* 1995). To our knowledge, the relative importance of shading versus other sources of seabed impact has never been conclusively established, and to do so would require targeted manipulative experiments. Despite the absence of clear evidence for adverse effects from shading, such impacts are nonetheless theoretically possible, as indicated by Hewitt *et al.* (2006) for a proposed oyster farm in Kaipara Harbour. Shading effects are conceivably of most importance where oyster farms are placed across seagrass and algal habitats in environments of relatively high water clarity, and in locations (*e.g.* well-flushed systems) where other ecological effects (especially those from sedimentation and biodeposition) are minimal. Shading effects on seagrasses and macroalgae can effectively be mitigated through appropriate farm placement.

3.3.6. Contaminant inputs

Operational oyster farms do not require the ongoing input of materials that could introduce trace contaminants to the marine environment, as can occur for example as a result of anti-fouling paints or synthetic feed inputs to sea-cage fish farms (Morrisey *et al.* 2000; Easton *et al.* 2002; Schendel *et al.* 2004). However, oyster racks may be constructed from treated timber (*e.g.* with copper, chromium and arsenic) that has the potential to leach contaminants into surrounding waters. Highly localised effects on sediments have been described in the vicinity of marine pilings as a result of such leaching (Weis *et al.* 1993), consistent with expectations that trace metals that are released to the water column will rapidly bind to suspended sediment particles. Sediment binding of contaminants is likely to reduce the potential for toxic effects on associated biota (Förstner 1995), and the release of contaminants from treated timber in seawater is reported to decrease over time (Brooks 1996; Breslin & Adler-Ivanbrook 1998). Hence, this issue is probably of negligible significance in the case of oyster culture sites where wooden racks are used. We note that farmed shellfish are subjected to metals testing as part of water quality programmes, which would presumably detect biologically relevant accumulation should it occur. Nonetheless, there is an increasing trend overseas to use alternative construction materials, or to develop strict regulatory guidelines around the use of treated timber for oyster farm structures (*e.g.* DPI 2008).

3.3.7. *Seabed effects following farm removal*

Recovery rates of seabed communities from deposition-related enrichment effects of oyster farms are unknown, but are likely to be relatively rapid once farming ceases. Based on observations of temporal change in benthic effects from oyster farms in New Zealand (Forrest 1991, unpub.), and literature for mussel and fish farms (Mattsson & Lindén 1983; Karakassis *et al.* 1999; Brooks *et al.* 2003; Pereira *et al.* 2004), conceivable time scales of recovery range from a few months in well-flushed areas where effects are minor, to a few years in poorly flushed areas where moderate/strong enrichment has occurred. Accumulated shell, sticks and other inorganic debris from intertidal oyster culture may persist for many years after the cessation of farming (Forrest & Creese 2006); hence the introduction of these novel habitats may result in fundamental or long-term shifts in seabed community composition. There is likely to be site-specific variation in the significance of this change according to environmental conditions, oyster species and density, and the extent of accumulation. The wider ecosystem consequences of such habitat changes, and the ecological role of farm structures themselves, are discussed further below.

3.4. Oyster cultivation effects on the water column

3.4.1. *Effects of farm structures on currents and waves*

Currents and waves play an important role in ecosystem function, particularly with regard to the transport of dissolved nutrients and seston (small particles and plankton) and nutrient exchange at the seabed-water interface. In relation to shellfish farming, currents and waves play an important role in the delivery of particulate matter and dissolved oxygen, and the flushing of wastes and associated nutrients into and out of the localised environment. If currents are not above a critical threshold to allow dispersion and resuspension of seabed sediments and associated detrital material from shellfish farms, for example, excessive accumulation of organic wastes and associated enrichment effects could occur.

Although there appears to be little published information for oyster farms, the farm structures and farm-related alterations to seabed topography (*e.g.* from shell accumulation) are likely to lead to effects on waves, currents and flushing characteristics in the vicinity of farm sites (Gouleau *et al.* 1982; Nugues *et al.* 1996; Hewitt *et al.* 2006). The structures themselves would be expected to baffle waves and currents, which in turn would enhance settlement and accumulation of particulate matter within close proximity of the farm. The effects of intertidal farm structures would be expected to have a proportionally greater effect on currents and waves than a subtidal structure, mainly due to the fact that the racks occupy a larger portion of the water column when submerged at high tide than a fully subtidal structure (see Section 2.4.1).

Literature for oyster reef habitats indicates that flow changes across the seabed may alter fluxes of materials (*e.g.* sediments) to adjacent habitats, and influence ecological processes such as patterns of dispersal and recruitment of invertebrates and fish (Breitburg *et al.* 2005; Ruesink *et al.* 2005). Effects of this general nature are also conceivable in the case of intertidal oyster culture, although specific differences can be expected given that the extent to which flows are modified will differ for different types of structure (*e.g.* because of differences in 'porosity' of structures as described in Section 2.4.1).

3.4.2. *Seston removal and alterations*

Natural oyster reefs are considered to have the potential to improve estuarine water quality by filtering seston from the water column (Gottlieb & Schweighofer 1996; Ruesink *et al.* 2005; Grizzle *et al.* 2006). As a consequence, there is much interest in the restoration of degraded oyster reefs as a means of top-down control of phytoplankton densities in eutrophic estuaries (Newell 2004; Cerco & Noel 2007; Newell *et al.* 2007; Pomeroy *et al.* 2006, 2007). Whether intertidal oyster cultures have comparable benefits is unknown. On the basis that the filter-feeding capacity provided by oysters (and associated fouling) is likely to represent a considerable increase above and beyond that provided by filter-feeding benthos in the same area prior to cultivation, such effects are arguably possible.

The adverse effects of intertidal culture systems on water quality in estuarine environments are less well understood, but are likely to be relatively minor given that seabed enrichment is low and external contaminant inputs are minimal, as described above. We are unaware of any water quality data for New Zealand oyster farms that indicate adverse effects on water quality. The only cases of adverse water quality effects from oyster aquaculture arise from overseas examples of suspended cultivation where farms are over-stocked or located in poorly flushed environments. Early studies of suspended subtidal culture of Pacific oysters in Japan revealed adverse water column effects that were related to excessive biodeposition on the seabed (Ito & Imai 1955; Kusuki 1981). For example, Ito & Imai (1955) described seabed enrichment so severe that oyster culture areas became 'self-polluting' (*i.e.* leading to oyster mortality) as a result of dissolved oxygen depletion in the overlying water column and the associated release (from sediments) of hydrogen sulphide at toxic concentrations.

By contrast, a study in Marennes-Oléron Bay (a major Pacific oyster culture area in France) suggests that mortality occurs as a result of a range of factors, and not simply a negative feedback of water quality (Soletchnik *et al.* 2005). The findings of the latter study further indicate that the potential for adverse water quality-related effects in the case of intertidal culture is low, which is perhaps not surprising considering that intertidal farm sites are substantially or completely flushed approximately twice daily with every low tide. Any water quality effects associated with intertidal culture can undoubtedly be minimised by appropriate site selection and farm design (*e.g.* ensuring that farm structures are configured in a way that causes minimal retardation of flushing processes).

Ecological carrying capacity

Oysters can filter particles within the 4–100 µm size range (Hawkins *et al.* 1998; Dupuy *et al.* 2000), hence can derive nutrition from phytoplankton (predominantly), detritus, bacteria, protozoa, zooplankton, and resuspended benthic microalgae (Le Gall *et al.* 1997; Dame & Prins 1998; Leguerrier *et al.* 2004). There has been considerable research into food depletion and modelling of ecological carrying capacity for oyster culture (Ball *et al.* 1997; Bacher *et al.* 1998; Ferreira *et al.* 1998) as well as for other bivalves and polyculture systems (Carver & Mallet 1990; Prins *et al.* 1998; Smaal *et al.* 1998; Gibbs *et al.* 2002; Nunes *et al.* 2003). Typically, this work has focused on phytoplankton depletion and maximum production capacity within growing regions. In this respect a number of indicators of carrying capacity have been used, in particular water residence time in relation to bivalve clearance and primary production time within a system (Dame & Prins 1998; Gibbs 2007). The literature in this field primarily addresses the role of natural or cultivated bivalve populations, whereas the filter-feeding activities of fouling organisms and other biota associated with shellfish cultures can also be functionally important (Mazouni *et al.* 2001; Mazouni 2004; Decottignies *et al.* 2007).

Influences from oyster aquaculture on estuarine carrying capacity are inextricably linked to the issues of nutrient cycling, seston depletion, and coupling between the water column and seabed. Interactions between shellfish cultivation, and the water column and seabed environments are complex, however, there is compelling evidence that bivalve aquaculture can affect nutrient cycling and the quantity and quality of seston across a range of spatial scales from local to system-wide (Prins *et al.* 1998; Cerco & Noel 2007; Coen *et al.* 2007). Control of Pacific oyster growth by phytoplankton availability has been described for subtidal floating culture systems in environments with long residence times such as Thau Lagoon in southern France (Souchu *et al.* 2001). In relation to elevated intertidal culture, Marennes-Oléron Bay has been described as "…one of the few systems where bivalve filter feeders have on two occasions been overstocked and overexploited" (Dame & Prins 1998). Marennes-Oléron Bay is a highly turbid system where bivalve clearance times are shorter than primary production and water residence times, and where resuspended benthic microalgae are an important food source (Dame & Prins 1998). There are anecdotal reports that Pacific oyster production in New Zealand estuaries has also been limited by carrying capacity, although this has not been definitively proven (Handley & Jeffs 2002, unpub.). The potential for such effects is invariably situation-specific and temporally variable. For example, the standing stock of phytoplankton and concentration of other SPM in estuaries is likely to be influenced by factors operating from tidal time scales to longer term climatic events such as El Niño Southern Oscillation cycles (Dame & Prins 1998; Prins *et al.* 1998; Zeldis *et al.* 2000).

Evidence (albeit limited) that seston depletion from oyster culture can reach or exceed carrying capacity at bay-wide scales suggests that wider ecosystem effects are also possible. Such effects could conceivably arise not only as a function of depletion, but also through alteration in seston size spectra and plankton species composition. In turn this could affect the quantity and quality of food available to other consumers (Prins *et al.* 1998; Dupuy *et al.* 2000; Pietros & Rice 2003; Leguerrier *et al.* 2004), with consequences for local populations of higher trophic level organisms such as fish. Food-web modelling for Marennes-Oléron Bay predicted a shift from pelagic to benthic consumers as a result of intertidal trestle cultivation of oysters, reflecting SPM depletion in the water column and enrichment of benthic meiofauna (Leguerrier *et al.* 2004). It is conceivable, therefore, that intensive oyster cultivation could have flow-on effects throughout the food web; however, the scant literature in this field does not provide any evidence for adverse effects (see Sections 3.5.2 and 3.5.3).

3.4.3. Seawater nutrient chemistry

The effects of intertidal oyster cultivation on seawater nutrient chemistry are poorly understood. Based on information from other bivalve culture systems, and natural or restored oyster reefs, it is evident that effects will be determined by processes involving filter-feeding and dissolved nutrient excretion, biodeposition and sediment remineralisation of nutrients, and loss of nutrients through oyster harvest (Newell 2004; Porter *et al.* 2004; Su *et al.* 2004; Prins *et al.* 1998). The production of dissolved (hence bioavailable) nutrients can occur directly via excretion by the oyster stock (Boucher *et al*. 1988), or indirectly via re-mineralisation and subsequent release from enriched sediments (Souchu *et al.* 2001). The subsequent effects of dissolved nutrient production on algal production involve complex interactions that are likely to be highly variable in relation to factors such as flushing, temperature, water clarity, stocking density, and the level of seabed enrichment. For example, although oysters may deplete phytoplankton, dissolved nutrients released from oyster excretion or sediment remineralisation have the potential to offset this effect by simultaneously stimulating phytoplankton production (Prins *et al.* 1998; Pietros & Rice 2003). Conversely, where filter-feeding by oyster reefs leads to locally increased water clarity (Cerco & Noel 2007), this may lead to increased production of benthic algae and seagrasses, thereby reducing the flux of dissolved nutrients to the water column and reducing phytoplankton production (Souchu *et al.* 2001; Newell 2004; Porter *et al.* 2004). For example, modelling by Cerco & Noel (2007) predicted that increased water clarity resulting from restoration of oyster reefs would lead to an increased biomass of submerged aquatic vegetation. For intertidal culture systems that are elevated, however, decreased sediment shear stress beneath racks, combined with turbulence induced by culture structures, may lead to enhanced sediment resuspension and high turbidity (Forrest & Creese 2006; Leguerrier *et al.* 2004). Clearly, nutrient cycling and related water quality attributes are influenced by complex environmental relationships and need to be further considered for intertidal culture in estuarine systems.

3.5. Wider ecological issues

3.5.1. *Habitat creation by farm structures*

Marine farm structures and artificial structures in general, provide a three-dimensional reef habitat for colonisation by fouling organisms and associated biota (Costa-Pierce & Bridger 2002). In a manner similar to that described above for the accumulation of oysters and debris, such structures provide a novel habitat that can support a considerably greater biomass and density of organisms than adjacent natural soft-sediment habitats (Dealteris *et al.* 2004; *Crassostrea virginica* cages). It is also well recognised that assemblages on artificial structures can be quite different from those in adjacent rocky areas (Glasby 1999; Connell 2000), and comprise a diverse assemblage of macroalgae and filter-feeding invertebrates (Hughes *et al.* 2005). Hence, several studies have highlighted the role played by artificial structures within the ecosystem, such as increasing local biodiversity, enhancing coastal productivity, and compensating for habitat loss from human activities (Ambrose 1994; Costa-Pierce & Bridger 2002; Hughes *et al.* 2005). These types of ecological roles are recognised for natural oyster reef habitats and on-ground oyster culture, as noted earlier in this paper.

Recent evidence also suggests comparable roles for suspended subtidal oyster culture structures (Lin *et al.* 2007), intertidal trestles (Hilgerloh *et al.* 2001) or other intertidal structures used for oyster cultivation. For example, Dealteris *et al.* (2004) concludes that oyster cages used for the grow-out stage of *Crassostrea virginica* have a habitat value that is considerably greater than non-vegetated seabed and at least equal to seagrass. It is also evident that some intertidal culture systems provide a habitat that can be extensively colonised by naturalised oysters, as described for *C. gigas* in western France (Cognie *et al.* 2006).

3.5.2. *Effects on fish*

The aggregation of various fish species around marine farms and other artificial structures is well recognised (Relini *et al.* 2000; Gibbs 2004; Einbinder *et al.* 2006; Morrisey *et al.* 2006), reflecting the role of such structures offering shelter from predation, habitat complexity and a food source. In New Zealand, there has also been discussion of the potential negative effect of cultured oysters and mussels on fish populations, primarily due to the consumption of fish eggs (Gibbs 2004.). The association of fish with on-ground oyster culture (versus rack or stick culture as is the case in New Zealand) has been described in a number of studies (Grabowski 2004 and references therein), and in fact a wide suite of ecosystem services from the restoration of oyster reefs are recognised (Coen *et al.* 2007 and references therein). Similarly, in the case of on-ground clam culture in the United States of America, Powers *et al.* (2007) found that the emergent habitat provided by fouling of mesh bags led to densities of mobile invertebrates and juvenile fish that were elevated by comparison with adjacent sand flats, and comparable to seagrass beds.

Conceivably, therefore, the ecological role of elevated oyster farm structures, combined with habitat alterations from the deposition of oysters and associated debris, may affect fish populations in a number of ways. However, a body of published information from primary literature comparable to that describing the effects of oyster reef or on-ground culture systems is unavailable for elevated culture systems, and the limited information available is equivocal. For example, Dealteris *et al*. (2004) describe a greater association with submerged aquaculture gear by some fish species but not others. Similarly, Dumbauld *et al*. (2009) cite Weschler (2004) who found no overall increase in fish richness or abundance adjacent to oyster racks, but a greater prevalence of structure-oriented species. Trophic modelling in Marennes-Oléron Bay represents one of few attempts to understand the wider ecosystem role of elevated intertidal oyster (*Crassostrea gigas*) culture (Leguerrier *et al*. 2004). These authors suggested that oyster cultivation could increase the food supply to fish, which was predicted to occur as a result of increased meiofaunal production. Similarly, increased turbidity (e.g., induced by erosion around oyster farm structures) may provide refugia from predation for small or juvenile life-stages of fish (*e.g.* Chesney *et al*. 2000; Leguerrier *et al*. 2004). A field mesocosm study of Pacific oyster cultivation effects in western France showed that the microhabitat created beneath trestles was more frequented by flatfish than adjacent homogenous habitat (Laffargue *et al*. 2006). More recently, an experimental scale deployment of oyster cages suggested that aquaculture gear could benefit populations of ecologically and economically important fish and epibenthic macrofauna in a way comparable to oyster reef habitat (Erbland and Ozbay 2008). Similarly, Lin *et al*. (2009) described an unexpectedly large decline in the biomasses of zooplanktivorous and piscivorous reef fish following the removal of an extensive area of high density oyster racks (up to 2932 racks/km^2), although field-based sampling was limited in their study. These authors suggested that the oyster racks might have previously attracted reef fish by reducing predation or enhancing their food sources.

3.5.3. *Effects on seabirds*

Overview

There appear to be no New Zealand studies on the effects of oyster cultivation on seabirds. Based on overseas literature, and knowledge of mussel farm effects in New Zealand, it is evident that effects on seabirds conceivably arise due to the alteration of food sources, displacement of foraging habitat and as a result of disturbance (*e.g.* noise) related to farm activities (Kaiser *et al.* 1998, Connolly & Colwell 2005). The additional issue of entanglement has been widely discussed in New Zealand in relation to mussel farming (Section 2.5.3) and other forms of aquaculture or fishing practice (Taylor 2000a,b; Butler 2003; Bull 2007), but is unlikely to be an important consideration for intertidal oyster culture. Entanglement primarily arises where loose or discarded rope is present, hence is highly unlikely in oyster cultivation where fixed structures are primarily used. Similarly, the effects of plastic and other marine debris on seabirds have received attention both internationally and in New Zealand (Section 2.5.3) but we assume that such problems are minimal or non-existent in well maintained oyster farms.

Effects on food supply

The recognised role of marine structures in providing fish habitat (see above) could conceivably attract bird species to prey items. Griffen (1997, unpub.) suggested that the habitat enhancement provided by natural seabed oyster reefs may benefit some bird species (*e.g.* herons and other foraging birds) by providing an additional food supply. This view is supported by recent work in Argentina which examined the ecological role of naturalised Pacific oysters 20 years after their introduction (Escapa *et al.* 2004). The latter study revealed higher densities of local and migratory birds, and higher foraging rates, inside oyster beds compared with reference areas, which were attributed to greater prey availability. In the case of elevated intertidal culture, trophic modelling by Leguerrier *et al.* (2004) similarly suggested that birds could benefit from an enhanced food supply. Clearly, the consequences for higher trophic level animals that arise as a result of intertidal oyster farm effects on the nature, quantity or availability of their food supply will depend on consumer dietary preferences and their ability to adapt to changes induced by cultivation. Overall, the few overseas studies of oyster culture provide information consistent with other forms of aquaculture described overseas, suggesting an attraction of seabirds to culture areas for foraging fish and epibiota fouling structures, and even the cultured crop itself (Ross *et al.* 2001; Roycroft *et al.* 2004; Kirk *et al.* 2007).

Effects on foraging ability

Despite their potential to provide food sources for birds, the large areas of estuarine habitat that may be occupied by intertidal oyster farms means that they also have the potential to displace seabirds from foraging sites. The evidence for this is limited, and suggests effects will be species and situation-specific (see Dumbauld *et al*. 2009 and references therein). For example, Zydelis *et al.* (2006) suggested that shellfish culture racks or stacked bags/nets could block large intertidal regions from wading shorebirds such as oystercatchers, plovers, stilts and potentially dotterels. Certainly, for some bird species there is evidence from overseas studies of avoidance or a decreased association with oyster structures compared with open tidal flats (e.g. wintering shorebirds in California; Kelly 2001). Conceivably any bird species that avoid structured habitats may be susceptible to displacement effects. However, the published international studies directly investigating interactions between elevated oyster culture and birds provide little evidence for significant adverse effects.

A number of studies have found that instead of local bird species being excluded from foraging sites, their distribution was unaffected and they were actively exploiting cultured species as a food source (Carswell *et al.* 2006; Zydelis *et al.* 2006). A study of intertidal cultivation in California concluded that oyster long-lines did not negatively affect the foraging behaviour of most bird species, but rather enhanced it; there was a greater diversity of birds, and a greater density of some species of shorebird and wading bird, in long-line plots compared with controls (Connolly & Colwell 2005). In relation to trestle culture in Ireland, a preliminary study by Hilgerloh *et al.* (2001) found that oyster structures did not affect the feeding behaviour of birds. For most species, bird densities were lower in the farm area than a reference area; however, the authors recognised that this pattern may have reflected natural environmental differences. In addition to modifications to benthos, Hilgerloh *et al.* (2001) also noted that macroalgae fouling the oyster trestles and associated small mobile gastropods provided a food source for some species.

Human disturbance

Disturbance of seabirds as a result of farm operations (*e.g.* noise and boat traffic) is an additional issue that should be considered for birds. Disturbance from noise and traffic does not appear to have been investigated in relation to elevated culture in estuaries, nonetheless New Zealand and overseas studies have reported that certain seabird species are more sensitive to human presence and disturbance (Goss-Custard & Verboven 1993; Butler 2003; Roycroft *et al.* 2004). Overseas, for example, Goss-Custard & Verboven (1993) found that oystercatchers were disturbed by the presence of humans in foraging areas, but were also surprisingly flexible in their ability to effectively redistribute their foraging activities. In New Zealand, Butler (2003) found that nesting king shags in the Marlborough Sounds were highly susceptible to disturbance by boats, leading to part or complete abandonment of nests and chicks. Varying levels of response to boat disturbance have been reported for several different shag species in New Zealand depending on location and their activity (Brown 2001; Lalas 2001). Lalas (2001) concluded, however, that boat traffic alone was not a significant disturbance factor to king shag foraging and/or resting activities. Consideration of effects from human disturbance on seabirds during the planning and site selection stages would assist in mitigating effects.

3.5.4. Effects on marine mammals

Overview

There are a number of publications concerning interactions between marine mammals and aquaculture (Würsig & Gailey 2002; Kemper *et al.* 2003), from which it is apparent that potential effects on marine mammals include disruption of migration pathways (in the case of large cetaceans), displacement from feeding/breeding habitats, underwater noise disturbance, potential for entanglement and flow-on effects due to alterations in trophic pathways. For intertidal culture the significance of many of these potential interactions is unknown, and we are unaware of any New Zealand studies that have considered such issues for Pacific oyster cultivation. Conceivably, the potential for adverse interaction between intertidal oyster culture and marine mammals is minor in New Zealand, as there is probably minimal overlap between sites of intertidal cultivation and typical marine mammal habitat, as we discuss below.

Habitat exclusion

Watson-Capps & Mann (2005) reported significant habitat exclusion of Indian Ocean bottlenose dolphins (*Tursiops aduncus*) by pearl oyster farms in Western Australia, in a bay where racks were suspended or fixed to the seabed in relatively shallow water (~2-4 m). Tracks of individual dolphins showed that adult females tended to swim around or stay on the periphery of the farm boundary rather than travel through it. To our knowledge this is the only study that has focused specifically on oyster farms. Together with research on mussel aquaculture (Section 2.5.4), the study highlights that, while most cetaceans will not be completely displaced from a region as a whole, they may not utilise habitats occupied by aquaculture structures in the same manner as prior to a farm's establishment.

The nature of habitat exclusion will greatly depend on the type of culture method and the particular species of marine mammal present in the cultivation area. As such, site-specific knowledge is required in order to undertake a robust assessment of risks to marine mammals in a New Zealand context. We can only assume that the potential for overlap between marine mammals and intertidal oyster cultivation is minimal by comparison with subtidal suspended cultivation; farms located on tidal flats would only be accessible to marine mammals during periods of high tide. Nonetheless we recognised that marine mammals can use shallow habitats. For example, southern right whales (*Eubalaena australis*) and humpback whales (*Megaptera novaeangliae*) utilise New Zealand's shallow bays and protected beaches (*e.g.* they beach themselves to rub off fouling; D Clement, pers. obs.), and are vulnerable to obstacles within their migrating or feeding areas where they may remain for days to weeks (Kemper & Gibbs 2001; Kemper *et al.* 2003; Kraus & Rolland 2007). Field and captive studies have found that smaller dolphin species appear reluctant to swim through wooden structures or those with ropes (Kastelein *et al.* 1995; Watson-Capps & Mann 2005; Heinrich 2006). Pinnipeds (*i.e.* seals and sea lions) are perhaps the one marine mammal species that are unlikely to be excluded from habitats by the occupation of oyster farm structures. Effects of intertidal culture on mammals can be mitigated through farm placement and avoidance of areas heavily utilised by mammals.

Underwater noise

Underwater noise in the oceans has recently made headlines as a fairly widespread, yet largely unknown problem for marine mammals, particularly the larger whale species (Nowacek *et al.* 2007; Weilgart 2007; Wright 2008). Hence, knowledge of potential effects and noise-reduction technologies is likely to be important for present and future industry development. Currently, however, no New Zealand or overseas studies have specifically analysed noise production in association with aquaculture and marine mammals. In-water noise, especially vessel noise, is regarded as the primary issue of concern because of sound travel in the water column. Due to the intertidal location of cultivation, oyster farmers undertake most work during lower tidal conditions on racks when they are out of the water, in which case noise generation will not be a significant issue for marine mammals. The potential significance of in-water noise will depend primarily on the vessel traffic generated as a result of oyster farming relative to other activities. In general, we would expect that the level and persistence of any associated underwater noises with oyster farming (other than the initial construction) are likely to be insignificant relative to other forms of shellfish aquaculture and other underwater noise sources, such as commercial and recreational vessels.

Entanglement

Oyster farming in New Zealand can occupy a significant area of intertidal habitat, as discussed above, effectively creating a novel obstacle that resident marine mammals have to actively manoeuvre around (Würsig & Gailey 2002; Markowitz *et al.* 2004; Watson-Capps & Mann 2005). Relative to some forms of aquaculture or fishing activities where rope or nets are used, the chances for marine mammal entanglement as a result of intertidal cultivation in New Zealand are probably minimal given that structures are either rigid wooden racks, or strong plastic coasted wire under high tension (BST method, see Figure 16). Given the curious nature of most marine mammals, the entanglement risk associated with intertidal cultivation could conceivably include small dolphins or pinnipeds becoming wedged under rack structures. However, the likelihood of such adverse consequences is likely remote given that such effects have never been reported elsewhere in the world where intertidal cultivation is far more extensive.

Indirect effects
The potential for wider, more indirect ecosystem effects on marine mammals due to shellfish aquaculture include the interrelated issues of food-web interactions (Black 2001; Kaiser 2001; Würsig & Gailey 2002; Kemper *et al.* 2003), biotoxin and pathogen (disease) outbreaks (Geraci *et al.* 1999, Kaiser 2001), and antibiotic use (Buschmann *et al.* 1996; Kaiser 2001). While these potential indirect interactions between marine mammals and shellfish aquaculture have been considered in the literature (Würsig & Gailey 2002; Kemper *et al.* 2003), no indirect effects have been documented.

3.5.5. Biosecurity risks and biofouling pests

Background
The role of the oyster industry in the spread of non-indigenous species, biofouling pests, toxic or noxious microalgae (associated with biotoxin production and shellfish poisoning), and disease has long been recognised internationally. This is especially true in the case of macroscopic biofouling (Bourdouresque *et al.* 1985; Minchin 2007; Mineur *et al.* 2007; McKindsey *et al.* 2007), and associated organisms (*e.g.* Duggan 1979; Utting and Spencer 1992). A number of studies have also documented survival of toxic and nuisance microalgae as a result of aquaculture transfers (see mussel industry issues in Section 2.5.5), with overseas studies also highlighting the potential importance of oyster transfers (McKindsey *et al.* 2007). In fact, the introduction of *Crassostrea gigas* for aquaculture, and other oyster species to a lesser extent, is regarded as one of the most important pathways for the global spread of non-indigenous species (Verlaque 2001; McKindsey *et al.* 2007). Ruesink *et al.* (2005) estimated that more than 40% of non-indigenous marine species in Europe, the western United States, and North Sea may have been introduced by oyster aquaculture. Consequently, international transfers of shellfish for aquaculture are now subject to rigorous risk assessment procedures.

From a New Zealand perspective the sources of present day risk from oyster aquaculture are similar to that for mussel aquaculture, and relate to the potential for domestic spread of pest species by farming activities. Almost invariably, however, the initial introduction of the species to New Zealand will have occurred by vessel traffic (Cranfield *et al*. 1998). Below we discuss risks to natural ecosystems as a result of oyster cultivation and transfer, considering biofouling pests (and associated organisms) and diseases separately.

Spread of fouling pests via oyster aquaculture
The general ways in which aquaculture can contribute to the spread of pest organisms was outlined for mussel aquaculture in Section 2.5.5. Elevated or suspended structures (and

associated shellfish crops) provide ideal habitats for some species to proliferate at high densities (Carver *et al.* 2003; Lane & Willemsen 2004; Coutts & Forrest 2007), potentially acting as reservoirs for the subsequent spread of pest organisms. The association of pests with oyster cultivation is described for a number of algal species overseas such as *Codium fragile* spp. *tomentosoides*, *Sargassum muticum* and *Undaria pinnatifida* (Trowbridge 1999; Verlaque 2001; Mineur *et al.* 2007) and for biofouling invertebrates in New Zealand such as the sea squirts *Styela clava* and *Eudistoma elongatum* (Coutts & Forrest 2005, unpub.; Smith *et al.* 2007).

Existing and potential biosecurity risks from oyster farming in New Zealand

The actual role of oyster cultivation in New Zealand in the spread of pests is unknown, but some general comments can be made based on broader knowledge of aquaculture and marine biosecurity issues, including the discussion relating to mussel culture in Section 2.5.5. The spread of pest species from infested farm structures or oyster crops at local scales (*e.g.* within bays) is likely to be primarily driven by natural dispersal mechanisms; in particular the dispersal of planktonic propagules in water currents (Forrest *et al.* 2008). In contrast, spread at inter-regional scales often occurs via inadvertent transport with human activities (Minchin 2007). For example, infested material (equipment, seed-stock or crop) at an oyster farm, or associated service vessels, may be moved to other localities as part of routine aquaculture operations, as suggested for a proposed oyster farm development in Kaipara Harbour (Taylor *et al.* 2005). Based on studies with fouling pests associated with mussel culture in New Zealand (Forrest & Blakemore 2006; Forrest *et al.* 2007) and oyster culture overseas (Mineur *et al.* 2007), there is a high likelihood that associated fouling organisms will survive if such transfers occur without the application of treatments to reduce biosecurity risks. In this way, oyster farming activities may lead to the spread of pest organisms in natural habitats far from the point of first incursion, potentially leading to irreversible effects on natural ecosystems (Ruesink *et al.* 2005). We are unaware of any routine procedures in place for oyster farms in New Zealand to manage biofouling or other pest transfer risks. A heat treatment procedure for oyster spat was developed in response to the presence of the toxic phytoplankton species *Gymnodinium catenatum* in the Kaipara in 2000, but has not been used since and would apparently be invoked only if a similar incident recurred in a spat collecting area (Taylor *et al.* 2005).

Pacific oyster as a non-indigenous species

Pacific oysters cultured in New Zealand are non-indigenous, as is the case in many countries worldwide (Ruesink *et al.* 2005). After the arrival of Pacific oysters in New Zealand, they had spread to the Marlborough Sounds by 1977 (Jenkins & Meredyth-Young 1979) and to Tasman Bay by 1981, and thereafter continued to spread within these regions (Osborne 1991; Jenkins 1997). Their spread further south is considered to be limited by water temperatures that are too cool for successful reproduction. Naturalised populations of Pacific oysters throughout their New Zealand distribution can reach high densities in natural and artificial habitats of estuaries, ports and harbours. Similarly, Cognie *et al.* (2006) found that as much as 70% of the oyster stock in a Pacific oyster growing area of the French Atlantic coast comprised naturalised rather than cultured oysters.

While Pacific oysters may be invasive primarily in rocky habitats and artificial structures, there is also evidence that they can invade soft-sediment estuarine habitats both overseas (Cognie *et al.* 2006; Smaal *et al*. 2009) and within their distributional range in New Zealand (Jenkins 1997; Forrest B, pers. obs.). The dense aggregates of Pacific oysters which form through high spat settlement on intertidal shores are a familiar site in some areas. Pacific oyster reefs in New Zealand can accumulate mud, and sharp oyster shell can degrade coastal recreation (Hayward 1997). Naturalised Pacific oyster populations may also displace native species in New Zealand (Dromgoole & Foster 1983). Based on the many overseas studies cited above highlighting the structural and functional role of oyster reefs or cultures in natural ecosystems, it can be expected that dense aggregations of naturalised oysters have the potential to lead to significant ecological changes (arguably both adverse and beneficial) in habitats where they establish (*e.g.* as described for Pacific oysters in Argentina by Escapa *et al.* 2004).

3.5.6. Disease

There have been no documented (OIE listed, OIE 2001) serious parasites/pathogens of Pacific oysters in New Zealand (Diggles *et al.* 2002). Nevertheless several diseases and parasites associated with New Zealand Pacific oysters have been reported, most of which are also globally ubiquitous and pose some commercial threat to oyster production (especially in hatcheries). These include various species of flatworm and mud-worm (Handley & Bergquist 1997; Handley 2002) and herpes virus, which infects oyster larvae and spat. Summer mortalities of oyster seed have been linked to herpes virus in California but a causal association has not been confirmed (Friedman *et al.* 2005). More detailed information on these and other diseases documented overseas is provided in Appendix 2.

To date, New Zealand farmed Pacific oysters have not suffered significant or unexpected effects from indigenous pathogens such as APX, *Bonamia exitiosa*, rickettsia and digestive epithelial virosis. This supports findings reported elsewhere that Pacific oysters appear more resilient to some diseases (Elston 1993) suffered by other oysters. In the light of this and since there have been extensive pathology surveys on New Zealand Pacific oysters - with negative results - it is inferred that culture of pre-existing *C. gigas* in New Zealand is unlikely to pose a pathological threat. However, any new importation of *C. gigas* stock should be subject to examination and be sourced from a documented disease-free area. This is suggested because observations from overseas indicate that there is a risk of spreading disease via introduction of oysters for culture – particularly from Pacific oysters. See Appendix 3 for examples.

Although New Zealand may lack some of the diseases identified overseas, congenerics and others of close affiliations do occur in New Zealand waters and could be similarly affected. It follows that should New Zealand *C. gigas* suffer an incursion by an exotic disease, it is possible that oyster farms could assist in the spread of disease to other molluscan species. Despite this possibility, the effect of non-native species can be unpredictable. For example, Thieltges *et al.* (2008) reported that the presence of introduced Pacific oysters (*C. gigas*) and American slipper limpets (*Crepidula fornicata*) mitigated the effects of a trematode parasite on blue mussels (*Mytilus edulis*). It appears that the introduced oysters diverted the trematodes from their usual native hosts, thus reducing infection levels.

3.5.7. *Genetic interactions with naturalised oyster populations*

Aquaculture of oysters, and hatchery production of spat, invariably raises the issue of genetic interactions with naturalised populations. The pertinent issues and concerns in this regard, were discussed for mussels in Section 2.5.7 and in detail in Appendix 3. In the case of Pacific oyster cultivation, ecological effects on naturalised populations are not as relevant since Pacific oysters are non-indigenous to New Zealand. Furthermore, recent advances in breeding and the future production of triploid oyster spat that are sterile will likely eliminate effects associated with genetic interactions between naturalised, farmed and hatchery populations.

4. DEVELOPING AND POTENTIAL NON-FINFISH SPECIES

4.1. Overview

Subtidal cultivation of Greenshell™ mussels and intertidal cultivation of Pacific oysters currently dominate the non-finfish aquaculture industry in New Zealand. Although a number of other non-finfish organisms have recognised aquaculture potential (Table 4). At the time of writing, sea-based 'commercial' farming of other species was limited to two small paua (abalone) farms, and small scale operations for seaweeds and oysters (excluding intertidal), most of which are being co-cultured with mussels. A few other species (*e.g.* crayfish, kina, paua) are sometimes held in sea-based cages after being harvested from the wild, to either synchronise the sale, or 'condition' the animals, to achieve optimum market value. Although not technically aquaculture, most of the issues discussed for Greenshell™ mussel and Pacific oyster culture are equally applicable to these grow-out or 'sea-ranching' operations.

Experimental research is being conducted with a broader variety of species, some of which are undergoing growth trials on existing farms, usually alongside established mussel cultures. In addition to those noted above, other species include scallops, blue mussels, sponges, sea cucumber and geoduck (Table 4). In many instances, the commercial sensitivity of new species development is such that information is not freely disseminated. Moreover, the size, scarcity and relative newness of these industries generally means that any associated environmental effects have not been described or are not yet fully expressed; hence related literature is sparse or non-existent.

It is assumed that many of the environmental effects that arise from cultivation of these other non-finfish species will be common among farming that involves similar cultivation methods (*e.g.* backbone suspended culture) and/or involves organisms with similar feeding strategies (*e.g.* filter-feeding bivalves). This is because most of the effects described in Sections 2 and 3 stem from either feeding and waste products or the physical presence of the structures themselves. In the absence of information on the ecological effects of potential culture species, we provide some general guidance on the likely nature and magnitude of effects based on information from comparable species or culture methods. To facilitate this assessment, we broadly group the candidate species according to their trophic level (*i.e.* position in the food chain) as this has implications for the nature of farm wastes that are generated. This approach allows us to consider potential effects on the seabed and in the water column and how they may differ among species (*e.g.* greatest seabed effects are likely to occur for species that require external food inputs such as artificial diets). Only general comments can be made with regard to broader ecological issues, because the culture methods and environments are yet to be defined, and/or the issues are highly species-specific and poorly understood (*e.g.* disease issues, genetic interactions between cultured and wild stocks).

Table 4. Minor and experimental culture species in New Zealand, with reference to the current status of the activity in New Zealand.

Classification	Species	Current status	
	Pacific oyster (subtidal) (*Crassostrea gigas*)	Experimental trials being conducted on existing mussel farms. (image source: www.fish.gov.au)	
Filter feeders	Flat oyster (*Ostrea chilensis*)	Experimental. Recent Government investment to research hatchery and grow-out methods. (image source: www.fish.govt.nz)	
	Scallops (*Pecten novaezelandiae*)	Tried on small scale commercial. None successful to date. Subject to experimental trials.	
	Blue mussel (*Mytilus galloprovincialis*)	Usually considered a pest, but small volumes harvested as an incidental by-product of Greenshell™ mussel culture.	
	Sponges (Bath sponge *Heterofibria*)	Experimental trials being conducted in Marlborough Sounds	
Grazers	Paua (*Haliotis iris*)	At least two small scale commercial farms growing/holding paua in barrels (image source: www.fish.gov.au)	
	Kina (*Evechinus chloroticus*)	Experimental trials being conducted by NIWA (PGST Contract C01X0301) (image source: www.seafood.co.nz)	
Deposit feeder	Sea cucumber (*Stichopus mollis*)	Not farmed commercially. Experimental trials. Potential as integrated culture species.	
Scavenger	Crayfish (*Jasus edwardsii*)	Research and experimental trials being conducted by NIWA (PGST Contract C01X0301) (image source: www.lobster.co.nz)	
Primary producer (seaweed)	*Macrocystis pyrifera, Undaria pinnatifida*	Small level of farming/wild harvest of *Macrocystis*. For *Undaria* Industry development limited 'unwanted species' designation. (image source: www.starfish.govt.nz)	

4.2. Commonality of effects among species

The reviews of Greenshell™ mussel and Pacific oyster effects in this report, and other reviews of the effects of finfish and other types of aquaculture in New Zealand (Cole 2002; Forrest *et al.* 2007) highlight that for different species, culture methods and culture environments, a similar suite of ecological issues arises. In the following section we describe in broad terms for each of these main issues, how the nature and magnitude of ecological effects may differ among the candidate species, different culturing methods and new environments.

In overview, those issues that we consider to be primarily species-specific are seabed and water column effects, disease and genetic interactions. Issues dictated more by culture method or farm management are likely to be effects on higher trophic level organisms (*e.g.* seabirds, marine mammals), production of contaminants, and the creation of novel habitat and spread of associated pests. Below we discuss examples that illustrate these general points, and make comparisons with the known effects of shellfish (Sections 2 and 3) and finfish (Forrest *et al.* 2007) aquaculture in New Zealand (as appropriate) to provide some feel for the nature and magnitude of effects that could arise with new species. In Section 4.3 we provide additional detail on actual or potential effects for each of the candidate species.

Seabed and water column effects
The propensity for benthic and water column effects can be roughly determined by the diet and feeding mechanism of the candidate species, their waste production and their likely culture method. The cultivation of organisms that require external feed inputs (*e.g.* crayfish, paua) are likely to produce more waste products than cultivation of species that do not rely on external feeds (see Table 4). The combination of excreted waste and uneaten feed has a relatively high potential to adversely affect the local seabed, as is evident in the case of salmon farming (Forrest *et al.* 2007). Dissolved waste products (*e.g.* ammonia and nitrate) may also stimulate algal production in the water column. By contrast, the cultivation of organisms (*e.g.* bivalves and sponges) that filter food (*e.g.* phytoplankton) from the surrounding water column and deposit organic waste on the seabed has less potential to cause adverse effects. Nonetheless, in high density culture situations filter-feeding pressure can be sufficient to cause localised depletion of phytoplankton, and overseas studies reveal the potential for relatively pronounced seabed effects in certain environments. How this potential varies among filter feeding species is discussed in more detail in Section 4.3.1. The cultivation of seaweeds (macroalgae), which function at a lower trophic level and utilise only dissolved nutrients and sunlight presumably leads to minimal ecological effects.

Contamination
The two main sources of contamination from sea-based aquaculture stem from additives in feed inputs (if required), and leaching of chemicals from farm structures or structure coatings, such as antifouling paints or treated timber. Documented cases of contamination arising from forms of aquaculture other than fish farming (see Forrest *et al.* 2007) have been negligible. Contamination is considered a culture method specific issue due to its likely origin in farming structures and feeds. However, the types of structures used would need to be vastly different from those presently used in the mussel or oyster farming industries for any issues to arise.

Most of the other species considered here are based around modified long-line type methods (and materials) and as such are unlikely to induce appreciable chemical contamination. However, consideration is given to the likely feed input for farm species that require an externally derived food input (*e.g.* crayfish, paua and kina).

Effects on fish, seabirds and marine mammals

The effects of farming the species listed in Table 3 on wild fish populations is poorly documented; however, is likely to be less pronounced than those associated with finfish aquaculture, which involves addition of an external food source to the environment (e.g. Dempster *et al.* 2002, 2004). The effects of large offshore sites (*e.g.* >1000 ha) warrant separate consideration given the scale of these developments compared with existing operations. Furthermore, offshore developments tend to be situated within range of various inshore commercial fish species (see Sections 2.5.2 and 6.1.1).

Effects on seabirds and marine mammals are likely to depend primarily on culture method, farming practice and environment (*e.g.* extent of overlap with critical habitat), and cannot be predicted in the absence of specific information. In the case of marine mammal entanglement, the review in Sections 2.5 and 3.5 revealed that the risk of entanglement is related to culture method and farm management. For example, the use of fixed structures or lines under tension is less likely to lead to entanglement than loose rope or line. At this stage, the specific nature of the culture methods for most candidate species, and the environments in which they will be cultivated are unknown.

Biosecurity risks and biofouling pests

The creation of novel habitat for fouling organisms and associated biota is well recognised for marine farms and other artificial structures in the sea, as discussed in preceding sections of this report. To some extent the nature of the 'reef' community associated with such structures will be related to culture method, since the size of the structure, construction materials, and orientation of structures, are likely to facilitate colonisation by different types of assemblages (Glasby 1999; Connell 2000; Glasby & Connell 2001). Moreover, the association of non-indigenous or pest organisms with marine farms and artificial structures is well recognised (Glasby 1999). Marine pest 'risks' arise mainly transfer of seed-stock or equipment that can move pests beyond natural barriers to their dispersal. Hence, biosecurity is also a species-specific issue that will be exacerbated by industries that 1) have a high degree of transfer between regions, 2) involve species not naturally widespread or indigenous to the bay/region, and 3) do not have biosecurity protocols for stock or equipment transfer and management in place.

Disease

High density cultivation of organisms raises the potential risk of disease transmittance to the surrounding environment. The risks associated with farming of these minor and potential species listed in Table 4 will be similar to those outlined for mussels and oysters (see Sections 2.5.6 and 3.5.6), although the diseases themselves and their pathology will often be unique to a given species. Detailed information on diseases that affect the health of cultivated non finfish species is provided in Appendix 2.

Genetic interactions between cultured and wild stocks

Genetic issues associated with sea-based aquaculture arise from either the transfer of wild caught stock between regions or the transfer of hatchery-reared stock to the wild, both of which have the potential to irreversibly alter genetic profiles of wild populations. Risk of this occurring is dependant on some species-specific factors such as: the level of genetic structuring within the species (low level of structuring corresponds to low susceptibility), local genetic diversity (wild spawning mechanisms ensure adequate genetic mixing), and, in the case of established culture species (*e.g.* mussels), the pre-existing levels of transfers. Factors specific to risks associated with the transfer of hatchery reared stock to wild populations mostly concern the potential for creating a bottleneck in the gene pool. Risks are greatest if the introduced stock is genetically narrow, there is a high level of structuring within the wild population, and the farmed stock is introduced in large numbers (numerical pressure).

4.3. Specific effects associated with candidate species

4.3.1. Filter-feeding bivalves

Cultivation of filter-feeding bivalves, other than Greenshell™ mussels and Pacific oysters, is currently limited to experimental trials, research and incidental by-catch (*e.g.* blue mussel). Species with feasible techniques and/or the most potential include oysters (flat oysters (*Ostrea* (formerly *Tiostrea chilensis*) and subtidal cultivation of Pacific oysters (*C. gigas*), scallops (*Pecten novaezelandiae*) and the blue mussel (*M. galloprovincialis*). Note that Section 3 focused on intertidal cultivation of Pacific oysters and that subtidal cultivation is still evolving and hence is considered here.

There are a number of other bivalves with potential, such as cockles (*Austrovenus stutchburyi*), geoduck (*Panopea zelandica* and *Panopea smithae*), toheroa (*Paphies ventricosa*), tuatua (*Paphies subtriangulata*) and several surf clam species (*Mactra* spp., *Dosinia* spp. and *Bassina* sp.). However, these species occur naturally within substrate or a 'sediment matrix', which is difficult to artificially reproduce off the bottom and adversely affects the economic feasibility of culturing these species. With the exception of the geoduck, which has exceptionally high economic value, the culture of sediment-dwelling species is unlikely to extend beyond enhancement of wild populations in the near future; and as such, they are not considered any further in this review.

Transferability of effects among bivalves

The commonalities of the physiology and likely culture techniques of the bivalve species considered here are such that many of the issues described for the Greenshell™ mussel or intertidal cultivation of Pacific oyster are relevant. Filter-feeding bivalves all obtain their nutritional requirements by filtering out suspended organic particulates (primarily phytoplankton and detritus) from the water column. Some species such as scallops are more dependant on benthic microalgae that become resuspended near the sediment surface (Gillespie *et al.* 2000; Keeley 2001; Gillespie 2008); however, they would rely on similar food sources as mussels when cultured within the water column. Bivalves process particulates from the water column and release both 'faeces' and undigested material called 'pseudofaeces', which are slightly heavier than water and sink to the seabed. The potential for localised phytoplankton depletion would be dependent on the clearance rate for a given species and the densities at which they are farmed. The potential to cause organic enrichment of habitats on the seabed would in turn be influenced by the rate at which particulate matter was processed and deposited on the bottom.

All of the bivalves considered here are also broadcast spawners, which means they release gametes directly into the water column, where dispersal range is determined by duration of gamete viability and current speeds. Accordingly, there is potential for progeny to colonise adjacent natural habitats and for mixing of farmed and wild populations. The scope for this issue arising is both species-specific and site/situation-specific and will need to be considered as part of any assessment of environmental effects. Of particular importance is the means of procuring stock or 'seed', where wild sources inherently maintain genetic diversity. Significant outbreeding depression has not been observed with current primary (*i.e.* mussels) and secondary species (*i.e.* scallops, oysters) and the same is likely to be true for analogous forms of bivalve aquaculture.

Relative potential effects of main bivalve species

The most likely culture methods for oysters (Pacific and flat), blue mussels and scallops, employ variations to the suspended culture techniques that have been developed around the mussel industry. The relative environmental effects of culturing different densities of these bivalve species in suspension were considered recently by Gibbs *et al.* (2006) using available, pertinent physiology literature (Table 5). A hazard assessment was used to identify the major environmental interactions between bivalves and the surrounding marine environment and this highlighted several major risk pathways, several of which were through the feeding and excretory behaviour of the bivalve crop. Marginal differences between the transfer of material by the different species were investigated using a range of feeding models and environmental data from the Marlborough Sounds and Glenhaven Aquaculture Centre (Nelson). The key result was that mussels generally appear to exhibit the highest clearance and excretion rates of the bivalves considered (Figure 21). Similarly, biodeposition intensity greater than 400 g/day/1000 individuals occurred most frequently in mussels (40%) followed by, scallops (33%), cupped oysters (29%), flat oysters (11%), and finally clams/cockles (6%).

Table 5. Summary of literature used in Gibbs *et al.* (2006) comparison of density dependant effects associated with culturing potential bivalve culture species.

Group/species	References
Clams/cockles	Pfieffer *et al.* (1999), Teiaoro 1999, Bacon *et al.* (1998)
Flat oysters	Haure *et al.* (1998), Rodhouse & O'Kelly (1981)
Cupped oysters	Ren *et al.* (2000), Bacher & Baud (1992), Barillé *et al.* (1997), Bougrier *et al.* (1995)
Scallops	Keeley (2001), Laing (2004), Teiaoro 1999
Mussels	James *et al.* (2001), Hawkins *et al.* (1999), Cawthron unpublished

Overall, the model indicated that the substitution of Greenshell^{TM} mussel*s* with any of the other alternate species/groups proposed was unlikely to increase either the clearance of the surrounding water, the biodeposition of suspended matter or the amount of dissolved ammonia through excretion. In fact, on an equivalent numbers basis substitution with any of the alternate groups may reduce these interactions, especially where either flat oysters or clams/cockles are considered. The study concluded that other bivalves species such as scallops, oysters and cockles may be cultured at stocking densities equivalent to those used for mussels without posing additional risk to the marine environment.

The hazard assessment also identified that farming structures can potentially lead to changes in the surrounding environment through the alteration of water flows. Scaling analyses were performed that highlight the relative differences in cross-sectional areas posed by different farming methods (Figure 22). The results from this analysis indicate that the present mussel farming practices occupy a greater cross-sectional area by comparison with the other methods that are presently used. Hence there is little evidence to suggest that the stocking densities of other bivalve species using different growing techniques should be more overly restricted by comparison with present marine farming practices.

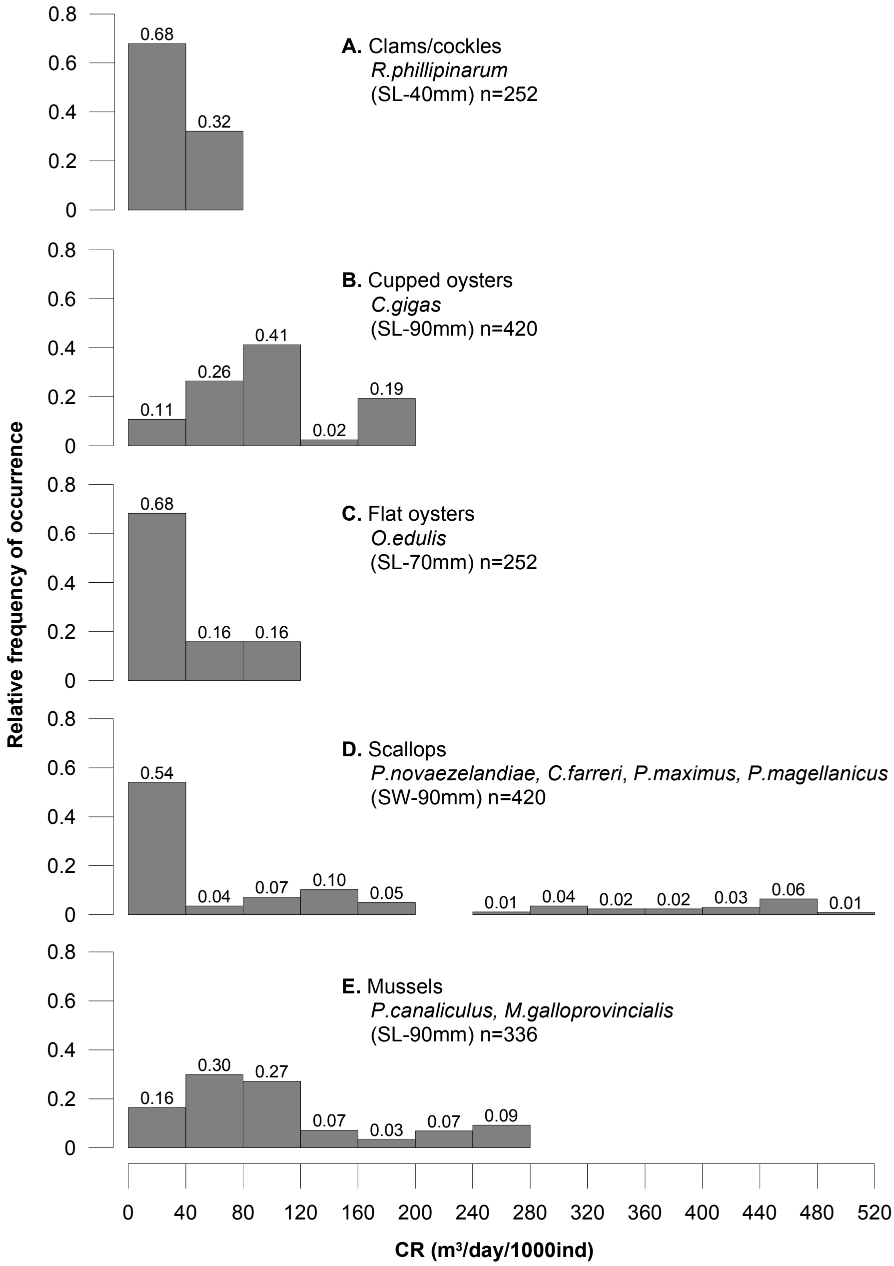

Figure 21. Comparative histograms showing the range and relative frequency of predicted clearance rates by bivalve group for the Glenhaven Aquaculture Centre ponds (from Gibbs *et al.* 2006).

A Side-on profiles.

B End-on profiles.

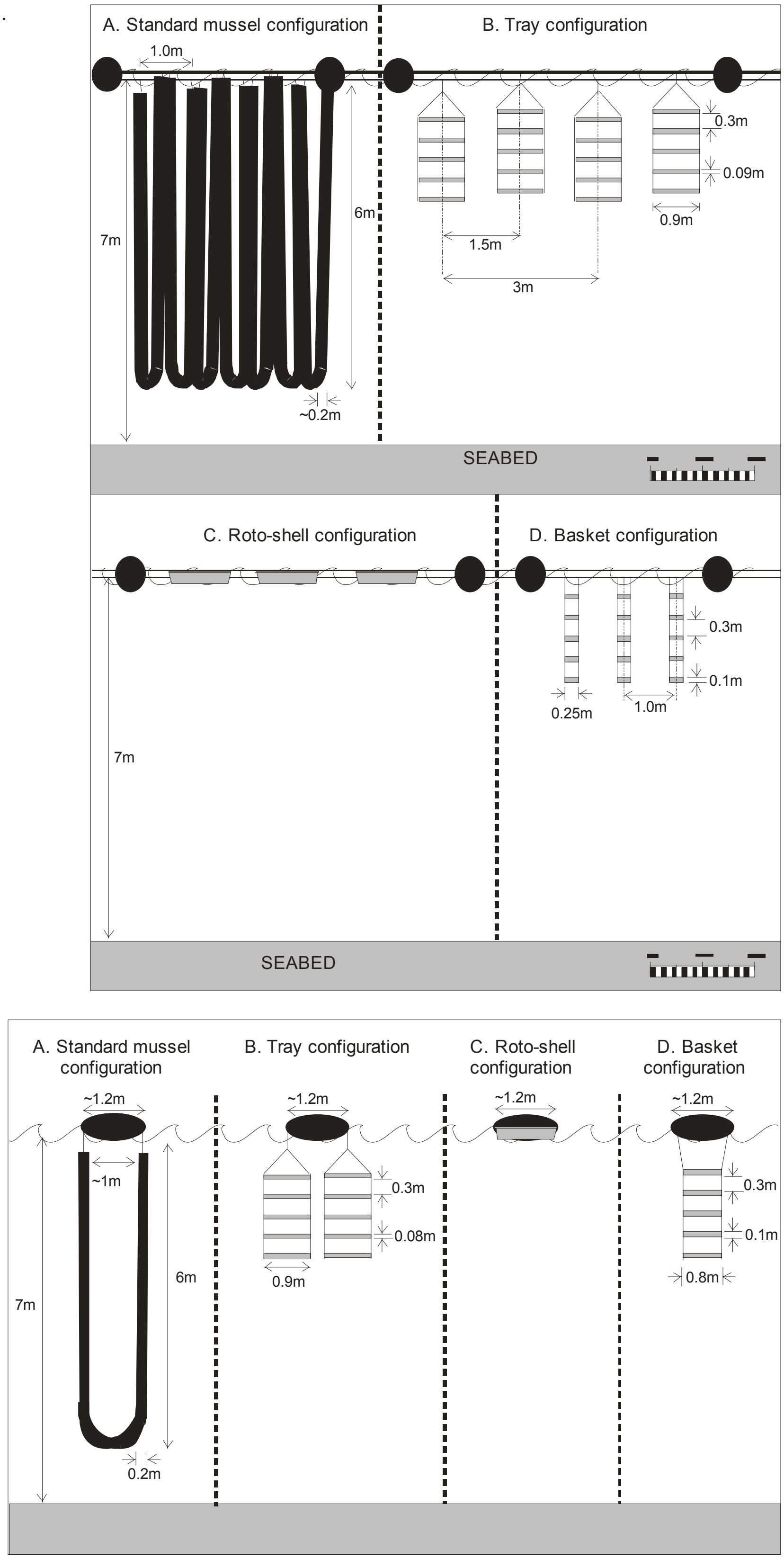

Figure 22. Scale drawings of potential culture configurations for the other bivalve species, considered by Gibbs *et al.* (2006). Specifications based on industry advice in 2006.

Pacific oyster (*Crassostrea gigas*) – subtidal culture

In New Zealand, Pacific oysters are traditionally cultured in the intertidal zone on racks or in baskets (see Section 3). Recently, there has been considerable interest in culturing Pacific oysters subtidally using a variety of innovative structures suspended from conventional long-lines. While still considered experimental, it is generally accepted that subtidal cultivation of Pacific oysters will be further developed.

Environmental effects arising from subtidal oyster cultivation are likely to be analogous to those described for subtidal mussels (see Sections 2 and 3) with perhaps some differences according to species-specific predisposition to diseases, genetic conditioning, biosecurity issues and ability to induce water column and benthic effects. As discussed in the previous section, the propensity for Pacific oysters to induce benthic or water column effects is expected to be comparable or less than that of other bivalve species such as Greenshell™ mussels. Disease and genetic issues for the Pacific oyster have been discussed in Section 3 and Appendix 2 and most of these findings are directly transferable to subtidal culture. The potential for disease transfer between oysters and mussels would need to be considered in cases of co-culture. It is also worth recognising that Pacific oysters are non-indigenous to New Zealand and considered by some to be an invasive pest species, mostly due to the access hazard they create around rocky shorelines. An important consideration with the development of this industry should be to ensure that it does not facilitate the spread of Pacific oysters to areas or regions that it is yet to colonise.

Flat oyster (*Ostrea chilensis*)

Although not commercially cultivated in New Zealand, *O. chilensis* has strong potential due to its highly regarded edibility that commands premium prices. Development of this industry has been hampered by difficulties in the larval production stages of culture (Jeffs & Creese 1996). Growth trials are presently being conducted using a modified long-line method in the Marlborough Sounds and the Cawthron Institute recently received Government funding to develop hatchery seed-production and grow-out techniques. Small commercial volumes are being produced on two farms in Southern New Zealand (Pers. Comm. M. Mandeno). If successful, flat oysters may become an important aquaculture species in the near future. Culture methods will most likely employ one of a variety of existing basket, purse or tray systems (see Figure 22) suspended from long-lines within existing AMAs.

Like *C. gigas*, *O. chilensis* belongs to the super-family Ostreacidae, and as such, shares similar physiological characteristics and presumably, a similar propensity for environmental effects. Although commercial culture techniques for the species are yet to be formally established, they are expected to be similar to those used for *C. gigas* and therefore create similar issues with respect to creation of novel habitat and associated wider ecological issues. Disease and genetic issues are however, likely to be species-specific and warrant some consideration. Unlike *C. gigas*, *O. chillensis* is native to New Zealand, which has potential implications for the transfer of disease and genetic material from farmed stock to wild populations. Wild (commercially fished) populations of *O. chilensis* have also experienced disease problems which may arise in a cultured environment. A summary of the disease literature is provided in Appendix 2.

Scallop (*Pecten novaezelandiae*)

The New Zealand scallop *P. novaezelandiae* belongs to the Pectenid super-family and like mussels and oysters, obtains its energetic requirements by filter-feeding (phytoplankton, diatoms and organic detritus). In the wild, scallops tend to be less aggregated and more widely dispersed than mussels and exist partially immersed in soft sediments. Over the last 20-30 years repeated attempts have been made to culture the species in suspension, but this habitat requirement has been difficult to replicate or overcome (Hayden 1998; Keeley 2001) and as such, commercially feasible culture methods have yet to be established. *P. novaezelandiae* does, however, grow off the seabed (Keeley 2001; Heasman *et al.,* in prep.) and is the subject of ongoing culture trials, and it is conceivable that the species will be cultured in the near future.

Environmental effects arising from scallop culture are likely to be analogous to those described for mussels. This is particularly true for most of the wider ecological issues. An exception to this may be the scope for shell drop-off, as scallops are mostly likely to be culture in cages or attached to substrates, in which case drop off would be minimal compared with mussels. Issues considered specific to this species include disease and ability to induce water column and benthic effects. The propensity of *P. novaezelandiae* to induce benthic or water column effects is compared with that of *P. canaliculus*, oysters and cockles in Section 4.2. Otherwise, actual studies that consider direct environmental effects of scallop culture are rare. An exception to this is Zhou *et al.* (2006), which described significant filtration pressure and enhanced biodeposition associated with intensive culture of the overseas scallop *Chlamys farreri*. Interestingly, the same study concluded that intensive scallop culture could be advantageous ecologically, by functioning as a biofilter and potentially mitigating eutrophication pressures. However, this argument only holds if over-enrichment is an issue, such as in Sushili Bay, China, where that study was conducted. By comparison, potential sites in New Zealand are nutrient poor and the culture methods far less intensive.

In terms of disease, experience from wild populations indicates that while numerous parasites are found in New Zealand scallops, none appear to present a serious threat and only a few have pathological significance. Among the more significant are digestive epithelial virosis (DEV), Rickettsia-like organisms (RLOs) and a new unidentified inclusion (Webb & Duncan 2008). No OIE (2000) listed diseases were reported. Disease prevalence and pathological significance in scallops are discussed in more detail in Appendix 2.

Blue mussel (*Mytilus galloprovincialis*)

Blue mussels (*M. galloprovincialis*) are cultured incidentally in significant quantities with Greenshell™ mussels on farms in the Marlborough Sounds. Although blue mussels are cultivated overseas, they are considered a nuisance species in New Zealand because of the issues they create (competition for resources, on-site fouling management, post-harvest sorting and disposal) for the culture of Greenshell™ mussels on which our marketing brand is based. However, a small volume of blue mussels do get processed and sold on the local market and if desired, *M. galloprovincialis* could easily become a major culture species. Its obvious suitability to conventional Greenshell™ mussel long-line culture techniques means it would inevitably be farmed in a very similar manner.

Blue and Greenshell™ mussels are both filter-feeding bivalves and share the same family, Mytilidae, and have an appropriately similar physiological make-up. Blue mussels tend to have smaller maximum and harvest sizes, and are reported to have similar food demands, as determined by clearance rates, rejection rates and energy requirements (Navarro *et al.* 1996; Hawkins *et al.* 1999). The absence of any monocultures of *M. galloprovincialis* in New Zealand means that literature pertaining to species-specific environmental effects has not been produced. However, given that the species is often (inadvertently) co-cultured in significant quantities on Greenshell™ mussel farms, any observed environmental effects associated with those farms must at least be partially attributable to *M. galloprovincialis*. Moreover, overseas studies of environmental effects resulting from suspended culture of *Mytilus* spp. (Hatcher *et al.* 1994; Heasman *et al.* 1998; Stenton-Dozey *et al.* 2001; Chamberlain *et al.* 2001) identify comparable benthic and water column issues to those described in Section 2; although in some instances they are more acute due to the relatively intensive raft culture techniques.

There is a general paucity of information surrounding disease threats associated with *M. galloprovincialis* in New Zealand. What information does exist, indicates little in the way of pathological problems, with the exception that invading *Mytilus* could act as a vector for facilitating the establishment of other serious exotic diseases. The species also has the potential to harbour viruses that may affect other species such as fish (Kitamura *et al.* 2007), but this is yet to be observed in New Zealand. Although poorly described, parasite fauna of *M. galloprovincialis* are likely to be comparable to that of the Greenshell™ mussel. More information relating to the pathology of the blue mussel is provided in Appendix 2.

4.3.2. Sponges and other low trophic level filter feeders

This group encompasses the 'simple' or low trophic level species, which filter particulate matter (bacteria and phytoplankton) from the water column. These organisms are typically sessile (fixed in place) and often encrusting by nature. Potential taxa within this group include a variety of sponges, ascidians, and hydroids, some of which have been examined for pharmaceutical properties (Page 2003), or physical properties in the case of the bath-sponge *Spongia (Heterofibra) manipulatus*. Sponges have also been considered for use in integrated culture systems as bioremediators of pathenogenic bacteria (Fu *et al.* 2005). New Zealand's experience with culturing these minor species is extremely limited and information pertaining to their culture is accordingly sparse. One exception is some recent work done with the bath-sponge in the Marlborough Sounds (Handley *et al.* 2003; Kelly *et al.* 2004), but no literature exits pertaining to the environmental effects of farming this or any other similar species. Hence the environmental effects of commercial culture of these types of organisms are poorly understood.

By comparison to other filter-feeders (*i.e.* bivalves), sponges exist naturally in low densities, but individuals can be large, and have high individual clearance and filtration rates. For example, a sponge with an 8 cm osculum (opening) can process 180 L seawater hr^{-1} and 1300 mg suspended solids hr^{-1} (Yahel *et al.* 2007) compared with 1-10 L/hr^{-1} and 1-1000 mg suspended solids hr^{-1} for an individual adult Greenshell™ mussel (Hawkins *et al.* 1999; James *et al.* 2001). In natural densities, sponges have been observed to alter the composition of the suspended particulates in the water column up to 0.75 m above the seabed (Yahel *et al.* 2007) so water column carrying capacity issues may be pertinent if cultured intensively. Presumably, sponges produce waste products, however, no information could be found detailing rates and composition of biodeposits. Commercial culture methods are yet to be established, but trials with *S. (H.) manipulatus* in the Marlborough Sounds utilised a modified lantern net design (Kelly *et al.* 2004). Many sponges favour exposed, or high flow environments that tend to coincide with rocky coastlines and reef habitats; hence, there is potential for overlap of aquaculture requirements with high value ecological habitats. There is also potential for biosecurity issues given the invasive nature of some ascidians, but these are negligible if the culture organism is native to the site.

4.3.3. Grazers and deposit feeders

This group of organisms is united by the fact that they either graze benthic algae (micro and macro) and/or eat detrital matter accumulated on the seabed.

Paua (*Haliotis iris*)

Paua (*H. iris*) aquaculture in New Zealand is mostly conducted in land-based systems, which can accommodate all phases of production (spawning, larval rearing, seed production and grow-out). Many hatcheries also now produce juveniles for reseeding and replenishment of wild stocks (Keeley *et al.* 2006). Both of these activities are beyond the scope of this report; however, there are presently at least two marine-based aquaculture operations (one in the Marlborough Sounds and one on Banks Peninsula) growing small amounts of paua, either for pearl cultivation or grow-out for harvest. Sea-based containment systems in New Zealand typically comprise barrels suspended from conventional backbone lines. Paua are grown inside the barrels where they are fed brown and/or red macro-algae (*e.g. Macrocystis pyrifera*, *Lessonia* sp., *Durvilliae and Pterocladia* spp.) and in some instances specially designed feed pellets. On at least one of the two existing farms, consent conditions specify that they can only feed paua the macro-algae that naturally colonises the farming structures, *i.e.* no artificial feeds or introduced biomass. Indeed, there is recognised potential for growing paua in a balanced, integrated co-culture system with algae, whereby minimal waste products are produced (Langdon *et al.* 2004). Abalone, are considered to be reasonably efficient feeders, assimilating approximately 80% of the food that is ingested (Bloomberg 1981; Peck *et al.* 1987; Yamasaki 1998). When in culture *H. iris* are fed at a daily rate equivalent to ~3% of their total body weight (Beatie 1998).

No robust studies could be found that describe actual environmental effects from culturing paua in sea-based containment systems. The two known farms in New Zealand are small in both scale and intensity, and function in a co-culture situation which makes species-specific assessments difficult. Some nutrient (ammonia and nitrate) monitoring is required by resource consent around at least one of these farms and we are advised that reported concentrations have been negligible. It is also worth pointing out that abalone are themselves considered to be highly sensitive to physical and chemical changes in their environment, and thereby demand maintenance of very high water quality conditions within the barrels. Wider effects to the water column are therefore inherently counter-productive to paua farming.

The 'potential' effects of farming paua have however been considered in the past for consent purposes (McShane 1997), and that report identified significant deposition and benthic enrichment issues. However, these findings were apparently based on incorrect feeding and stocking values, which were detrimental to the assessment (Beatie 1998). An alternative theoretical scenario is provided in Table 6 based on published assimilation rates and farming statistics detailed in Beatie (1998) to help gauge the relative potential for benthic effects. This relatively crude calculation suggests that a paua farm could conceivably produce waste products at a rate of ~2-20 kg m^2 yr^{-1} (dependant on animal size). The upper range of this estimate is comparable to that of modelled predictions for functioning salmon farms in the Marlborough Sounds (Keeley *et al.* 2006). It is therefore fair to assume that given sufficient scale and commercial intensity, waste production may be sufficient to induce deposition and enrichment related effects. As with other forms of aquaculture, the extent of these effects will be influenced by environmental and farming management practices (*e.g.* Section 2.3.5, Forrest *et al.* 2007), which need to be considered in an overall site assessment. It is possible for example, that such commercial intensities are impractical due to the water quality feedback mechanism discussed above.

Table 6. Parameters used in hypothetical scenario for calculating depositional output from a sea-based paua farm. (Stocking densities and feed rates from Beatie (1998), weight of individuals from McShane (1997), and feed assimilation rates average from Bloomberg (1981), Peck *et al.* (1987) and Yamasaki (1998)).

	Animal size		
Parameter	**75mm**	**15mm**	**Units**
Equivalent seabed density	127	952	ind·m^2
Size (individual)	75	15	mm
Weight (individual)	72	1	g·ind^{-1}
Total biomass	9144	952	g·m^2
Feed rate	3	3	% body weight·d^{-1}
Food assimilation rate	80	80	%
Feed in	274.3	28.6	g·m^2·d
Organic matter egested as faeces/	54.9	5.7	g·m^2·d
pseudofaeces = Depositional rate	20.0	2.1	kg·m^2·yr

Paua are broadcast spawners, which means gametes from adult farmed stock may mix with those of wild populations and farmed progeny may settle on adjacent natural coastline given suitable habitat. As long as good brood stock management protocols are adhered to, risks of genetic contamination issues arsing are likely to be small.

In terms of pathology, abalone are susceptible to a number of disorders, diseases, viruses and parasites (see Appendix 2), none of which are presently problematic in New Zealand paua. Of particular relevance, however, is a Tasmanian example where a farm-originated virus spread to wild abalone resulting in significant mortalities (Hine 2006). Good stock management and biosecurity practices and surveillance are obviously required with this species to help manage pathological threats. Specific mitigation actions should be devised from best practice elsewhere if diseases become established in New Zealand. A factor in our favour is that some parasites appear to have an indirect life cycle requiring a number of host stages. If any of these have been left behind and there are no local substitutes then the pathogen may not be sustainable. This possibility, while encouraging, is no basis for complacency and further work is required to allow more informed inferences.

Sea cucumber (*Stichopus mollis*)

Sea cucumbers are deposit-feeders, obtaining their nutritional requirements from processing large volumes of sediments on the seafloor, digesting the organic components (algae, diatoms, cyanobacteria) and excreting unwanted sediments (Uthicke 1999). They, therefore, require a sediment substrate and are not conducive to suspended culture. Recent experiments have used bottom-oriented cages (Slater & Carton 2007) with some degree of success and *S. mollis* has serious potential as a future aquaculture species. Presently however, juveniles would have to be hatchery spawned because *S. mollis* is not currently listed as harvestable spat under the Fisheries Act (1996).

Examples of sea cucumbers being cultured in isolation are rare, as are any studies relating to adverse environmental effects that can arise from their culture. Instead, studies of environmental effects associated with sea cucumbers tend to focus on their ability to mitigate the depositional effects from the culturing of other species. Hence, sea cucumbers are becoming a popular co-culture species with bivalve (*e.g.* oysters, Paltzat *et al.* 2008), paua (Kang *et al.* 2003) and fish farms (Ahlgren 1998). Sea cucumbers are presently not cultured commercially in New Zealand, but *S. mollis* is being investigated as a potential co-culture species with Greenshell™ mussels (Slater & Carton 2007). The mitigative potential of co-culture systems are discussed in more detail in Section 6.1.2. Other potential issues associated with culturing *S. mollis* remain undescribed and are unlikely to be realised until the species is cultured in significant quantities.

Kina (*Evechinus chloroticus*)

Aquaculture of kina in New Zealand is presently restricted to experimental research, and as such, studies relating to environmental effects from commercial-scale culture do not exist. Kina (also known as sea eggs) are sea urchins and belong to a large group of marine invertebrates called Echinoderms and are endemic to New Zealand. Aquaculture trials to date have utilised sea- and land-based cages, in which the animals are fed natural kelp, or specially formulated artificial feeds (James 2006). Much of the research (nationally and internationally) conducted to date has been oriented around factors which affect sea urchin roe enhancement (Klinger *et al.* 1997; James & Heath 2008; Woods *et al.* 2008). The diet that has been trialled most recently in New Zealand, by NIWA, is comprised mostly of protein-rich fish-skins, a fisheries by-product (Woods *et al.* 2008). In Scotland, urchins have also been used experimentally in polyculture systems beneath salmon farms where they were maintained successfully on excess fish pellets (Kelly *et al.* 1998). We note however, that most of the trials cited in this review were conducted on urchins sourced from the wild. The emphasis appears to still be on conditioning roe ready for market (*i.e.* finishing diets) and as such, the sea-based aquaculture component of this industry may be limited.

Environmental effects associated with kina culture are likely to be minimal as long as the scale and intensity are moderate, and probably akin to those of sea-based paua farming. There is also recognised potential for farming kina as a mitigative component in integrated aquaculture systems. Some potential for contamination issues exists if they are predominantly fed on artificial diets.

4.3.4. Scavengers and piscivores

This group is broadly united by the requirement of high protein diets derived from animals and animal by-products (*e.g.* fish, shrimps (brine), fish meal, shellfish *etc*.). Potential culture species included in this group are crayfish (*Jasus edwardsii* and *Sagmariasus verreauxi*), shrimp (various), seahorses (*Hippocampus abdominalis*), and paddle crabs (*Ovalipes catharus*). Culture of these species in New Zealand, is either in its infancy, or likely to occur in land-based systems and are therefore not encompassed by this review. The main exception to this is crayfish, which may be grown in sea-based cages, and have considerably more economic potential due to a consistently high market value.

Crayfish (*J. edwardsii*)
Increasing global demand, high economic value and concerns about the sustainability of the wild fisheries have ensured strong world-wide interest in developing culture techniques for crayfish or 'lobsters'. In New Zealand (and Australia), efforts have been focused on the primary wild-caught species, *Jasus edwardsii*. Commercial production has apparently been achieved (Sheppard *et al.* 2002), but hatchery production (from larvae) is still not feasible due to a long and complex larval development phase (Kittaka *et al.* 2005; Williams 2007). Instead, emphasis has been on on-growing wild-caught juveniles or 'pueruli' (Mills & Crear 2004). Commercial culture is, therefore, dependant on the effectiveness and reliability of capturing wild puerulus, and any large scale operations would likely have implications for the sustainability for the wild fishery. In the past this has been addressed by off-setting a set number of puerulus obtained from the wild against tonne of crayfish quota and requiring that a certain percentage of those reared are returned to the quota area from which the pueruli were obtained.

Not surprisingly, studies which specifically deal with environmental effects associated with farming crayfish are scarce. Our review of effects is, therefore, limited to an assessment of potential for inducing effects based on what is known about the likely culture methods. Defined as 'opportunistic carnivores', *J. edwardsii* can feed on a wide variety of invertebrates (Williams 2007), but in culture, can be sustained solely on mussels. Recently however, much effort has gone into formulating pelleted diets to optimise growth (Simon & James 2007; Williams 2007). As with other forms of aquaculture, it is these high-protein external feed inputs and the subsequent waste products that increase the scope for enrichment-related effects to the seabed and water column. Various cage configurations have been proposed, but growers generally conform to using surface-oriented structures with suspended cages that occupy the top 2-3 m of the water column and in a recent trial were stocked with 35 individuals/m^2. Enrichment-related effects will obviously also be scale and stocking-density dependent.

Although the gregarious nature of spiny lobsters coupled with access to abundant prey may make them robust to the pressures of high population density (Behringer & Butler 2006), disease outbreaks and mortality within caged populations can be an issue (Diggles 2001). It would therefore follow that the potential for disease transfer to wild populations is an issue worthy of consideration. In terms of potential to influence the genetics of wild fish from culture and transfer of farmed fish, the level of genetic structuring of *J. edwardsii* is thought to be relatively low due to the long planktonic larval phase, which potentially provides for extensive movement and gene flow. This occurs to the extent that there is thought to be some trans-Tasman larval flow (Chiswell *et al.* 2003) and that likely leads to the New Zealand and Australian populations being genetically indistinguishable (Ovenden *et al.* 1999). The risk of crayfish aquaculture influencing natural genetic profiles is therefore presently assessed to be low. It is possible however, that a more rigorous appraisal using new technology may well reveal something different (J. Gardner, pers. comm.).

4.3.5. Macroalgae (seaweeds)

Macroalgae derive their food requirements from dissolved nutrients and sunlight. A broad range of species are cultured worldwide for human consumption (*e.g.* nori, *Porphyra* spp.; wakame, *Undaria pinnatifida*; kombu, *Laminaria japonica*; phycocolloides), food products (e.g. agar, carrageen and alginates), pharmaceutical products and for use in agricultural feeds (Smit 2004). Despite the ~150 farms that have permits to culture seaweed (MFish, pers. comm.), the only species presently being utilised in New Zealand are the large brown algae *Macrocystis pyrifera* and the introduced brown algae *U. pinnatifida*. *M. pyrifera* is predominantly harvested from the wild, but also from an established AMA on Banks Peninsula. The volumes of *M. pyrifera* being harvested are small and it colonises the structures naturally, so can only be loosely described as aquaculture.

Likewise, *U. pinnatifida* is presently a "by-product" of the mussel industry, as it grows profusely on the upper parts of mussel lines. The aquaculture potential of *U. pinnatifida* has been researched by the Cawthron Institute (Hay & Gibbs 1996; Gibbs *et al.* 1998, 2000), but it is yet to be realised because it has been classed as an unwanted organism under the Biosecurity Act 1995. *U. pinnatifida* is also not in the QMS, and therefore has no TAC or TACC. Despite this, one marine farm in Mahanga Bay has been granted permission for *U. pinnatifida* aquaculture, and at least two companies now hold licenses to harvest the species. The estimated tonnage harvested from one of these sites (in the Marlborough Sounds) is 2,000 tonnes $year^{-1}$.

The environmental effects of algae culture in New Zealand remain undetermined due to the absence of commercial scale examples. Internationally, studies pertaining to adverse environmental effects from farming algae are also sparse. There is, however, a wealth of new literature considering the bioremediation potential of culturing algae in integrated systems and its ability mop up excess nutrients discharged from fish farms (Zhou *et al.* 2006a; Blouin *et al.* 2007; Kang *et al.* 2008; Xu *et al.* 2008). While macroalgae farming may be appropriate in a eutrophic system, or in conjunction with an artificial nutrient source, the high nutritional requirements could potentially affect the wider ecosystem in areas that are nutrient poor.

The light requirement of algae culture is likely to impose depth constraints on the culture methods in most situations. This in turn may create a tendency to densely occupy space on the horizontal plane at the surface, which would reduce the amount of light penetration lower in the water column and at the seabed, potentially resulting in localised primary productivity issues. Such effects have been identified from intertidal algae farms, which can impede growth in adjacent seagrass beds and alter the macrofauna community contained within (Eklöf *et al.* 2005). A subsequent study also demonstrated that algae farms can alter the composition of fish communities and potentially increase fish catches (Eklöf *et al.* 2005, Eklöf *et al.* 2006). These findings are however very much site-, situation- and species-specific. Algae farming in New Zealand is more likely to be conducted off the bottom, in deeper water, and as such, the scope for analogous effects will be reduced.

Perhaps the biggest potential environmental issue associated with algae culture relates to biosecurity, as there are numerous examples where introduced species of macroalgae have posed major threats to the surrounding ecosystem, and in some cases, other forms of aquaculture (Forrest *et al.* 2000; Neil *et al.* 2006; Schaffelke *et al.* 2006; Bullard *et al.* 2007). However, these threats are negligible if algae aquaculture is restricted to indigenous species.

5. EVALUATION OF ECOLOGICAL RISKS FROM NON-FINFISH AQUACULTURE

5.1. Frame work for risk assessment

Our review highlights several commonalities with regard to ecological effects associated with the subtidal cultivation of Greenshell^{TM} mussels and intertidal cultivation of Pacific oysters, particularly with regard to seabed and water column effects. Farming of minor or potential species of filter-feeding bivalves (scallops, flat oysters, subtidal Pacific oysters, blue mussels) is expected to have analogous effects on the marine environment, whereas the cultivation of organisms that require the addition of feed (paua, crayfish) may lead to different types or magnitudes of effects. The nature and magnitude of wider ecological effects such as the spread of pest species, disease outbreaks, or effects on the genetic makeup of natural populations will often depend on the species.

From the available information, and based on experience with other forms of aquaculture or from wider ecological literature, we consider that the key ecological stressors that lead to adverse effects are sufficiently recognised that they can be evaluated across the various forms of non-finfish aquaculture. Such an evaluation is useful in that it places the effects described in this report within a comparative "risk" context, which considers the magnitude, likelihood, spatial extent and duration (impact persistence over time) of an effect. Such an evaluation can also assist in identifying knowledge gaps and guiding management or mitigation strategies. Rather than attempt such an evaluation for all actual or potential aquaculture species described in this report, we provide by way of an example a summary of the analysis by Forrest *et al.* (2009) for intertidal Pacific oyster farming in New Zealand. That study evaluated the relative ecological significance of the range of issues discussed in this report, with the exception of marine mammals. Effects to marine mammals are not well evaluated by this type of risk frame work, as the likelihood of any adverse effect is very small (in fact we are aware no adverse interactions in relation to oyster cultivation in New Zealand) and the consequences highly species- and situation-specific. For example, the death of a single individual from a population of abundant and common animals (*e.g.* New Zealand fur seal) may have relatively limited significance. However, if that individual was a large reproductive adult from a small population of an endangered species, then the consequences could be profound.

Hence, except for marine mammal interactions, oyster cultivation risk for the other issues is evaluated for current levels of development in relation to three categories: (i) the magnitude of effects, including the likelihood and consequences of actual or potential effects; (ii) the spatial extent of effects from site-specific to regional scales; and (iii) duration; the length of time effects would persist if farming operations were ceased and farm structures removed. Within each category, ecological significance and uncertainty were ranked according to narrative criteria (Table 7). This exercise was undertaken by seven Cawthron scientists with a broad knowledge of the ecological effects of marine aquaculture.

Table 7. Narrative criteria used to compare relative level of knowledge and ecological significance of effects from elevated oyster culture.

Category	Low	Medium	High
Level of knowledge	Based on perception or inference from related studies	Based on limited information on effects of elevated culture	Specific effects of elevated culture known
Relative magnitude of effect	Minor	Moderate	Significant
Spatial extent of effect	Local scale (restricted to tens of metres from culture area)	Bay-wide (extending hundreds of metres from culture area)	Regional (kilometres or more from culture area)
Duration of effect	Short-term (abates immediately)	Medium-term (continues for months to a few years)	Long-term (continues for many years and may be irreversible)

The results of this evaluation (Table 8) **should be regarded as a guide only**, as they are intended to reflect *relative* risk (as derived from expert opinion) and in some cases are based on limited information. Furthermore, actual levels of risk will often depend on site-specific factors such as the intensity of farming in a given area, the sensitivity of the receiving environment, the presence of pre-existing stressors, and the extent to which mitigation is possible. Although we suggest that only major differences in risk scores are meaningful, the evaluation nonetheless facilitates general understanding of the ecological significance of the various issues at least in a relative sense.

5.2. Risk evaluation

Results of this exercise revealed that biosecurity issues relating to the spread of pest organisms received the highest risk scores (Table 8). This finding is consistent with an aquaculture risk assessment described by Crawford (2003) for Tasmania, and also with the general view that inadvertent pest introductions are one of the more significant issues associated with aquaculture in estuaries (deFur & Rader 2003). The reason is that, by comparison with all other risk categories, the spread of pest organisms by aquaculture activities can occur at regional scales, potentially leading to ecologically significant and irreversible changes to coastal ecosystems (Elliot 2003). Whether the spread of a given pest organism (or oysters themselves) by oyster farming activities (*e.g.* inter-estuary transfers of infected equipment or seed-stock) is conisdered significant depends on a number of different factors (*e.g.* relative risks from other pathways such as natural dispersal or fouled vessels). Furthermore, it is important to recognise that management plans and mitigation strategies may be developed to minimise biosecurity risks.

Seabed effects from biodeposition and debris, and potential effects of disease received the next highest relative risk scores. The effects of biodeposition and debris are the more obvious or conspicuous effects of oyster farms, and are reasonably well understood. In general, seabed effects can be moderately pronounced but highly site-specific, appear to extend no more than a few tens of metres from the perimeter of the farmed area at worst, and are likely to be reversible (should farming be discontinued) over time scales of several months to a few years, although debris accumulation could lead to long-term changes in habitat structure. Thus the wider ecosystem significance of seabed effects depends on the spatial scale of farming activity in relation to site-specific ecological values, such as the presence of species or habitats that are sensitive to impacts or are of special interest (*e.g.* high conservation values, keystone species). The potential for disease also scored relatively high; even though the likelihood was considered low the consequences could be high (hence magnitude medium), and include the potential for widespread and long-term effects.

Table 8. Summary of actual and potential effects from elevated intertidal oyster culture in relation to key risk criteria fromTable 7. Note that marine mammals were excluded from this assessment for reasons discussed in the text above.

Effects	Description	Knowledge	Magnitude	Likely spatial extent	Likely duration[a]	Relative risk rank
BENTHIC						
Biodeposition and enrichment	Altered sediments and enrichment of benthos	High	Low-medium	Lowl	Medium	Medium
Effects of debris and altered topography	Structural change to seabed habitat and effects on epibenthic communities	Medium	Medium	Low	High[b]	Medium
Physical disturbance	Seabed disturbance from farm operations	Medium	Medium	Low	Medium	Low-medium
Shading	Effects on benthic primary producers if present	Medium	Low- medium	Low	Medium	Low-medium
Contaminant inputs	Contaminant accumulation and ecotoxic effects	Low	Low	Low	Medium	Low
WATER COLUMN						
Alteration to waves and currents	Reduced flushing and increased sedimentation	Medium	Low- medium	Low	Low	Low
Adverse effects on water quality	Dissolved oxygen depletion and sulphide production	Medium	Low	Low	Medium[c]	Low
Nutrient cycling and seston depletion	Alteration to nutrient cycles and depletion of seston	Low-medium	Low- medium	Medium	Uncertain	Low-medium
OTHER						
Habitat creation	New habitat provided by farm structures	Low-medium	Low- medium	Medium	Uncertain[d]	Low-medium
Fish	Alteration to food sources, provision of novel habitat	Low-medium	Low- medium	Medium	Uncertain[d]	Low-medium
Seabirds	Alteration to food sources and foraging habitat, provision of novel habitat	Low-medium	Low- medium	Medium	Uncertain[d]	Low-medium
Pest species	Introduction and spread of	Medium-high	High	High	High[b]	High

	fouling pests and toxic or noxious microalgae					
Disease	Introduction and spread of parasites or pathogens	Medium	Low	High	High[b]	Medium

[a] Duration of effect assumes farming ceases and structures are removed
[b] Potential to mitigate the potential for long-term effects by managing risk
[c] Time-scale of recovery from adverse water quality effects may be linked to sediment recovery
[d] Uncertain; insufficient knowledge of effect duration to make assessment

There are a range of remaining issues relating mainly to water column and wider ecosystem effects for which ecological significance was on average scored as low or low-medium in a relative sense (Table 8). This generally concurs with the review of Dumbauld et al. (2009) who concluded that bivalve culture effects in US West Coast estuaries tended to be localised and short-term, and not associated with larger scale ecosystem changes. Feedback from the experts in the present work revealed that, even where the level of knowledge or certainty was regarded as low, relatively low scores were often assigned on the basis that effects had not been conclusively documented (*e.g.* seaston/food depletion), or were not judged as adverse (*e.g.* novel habitat creation). Clearly, in the latter case where this viewpoint is highly subjective, there is potential for greatly differing views, although in this instance the general consistency in views for most categories was reflected in a low variance around mean risk and knowledge/certainty scores (see Forrest *et al.* 2009). We also acknowledge the possibility that unrecognised estuary-wide or cumulative effects could have already occurred from some oyster farm developments, or could arise in the future, for example: (i) in situations of high-intensity oyster farming (*e.g.* if there are enclosed embayments dominated by oyster farms), or (ii) because of the occurrence of ecological values of high importance. Without knowledge of baseline conditions and subsequent changes post-farm development, many of the water column effects and wider ecosystem effects described in this report would be difficult to determine retrospectively.

The results from the risk assessment of oyster farming would be broadly transferable to the subtidal cultivation of Greenshell™ mussels and other bivalve species. Perhaps the main point of difference would be in relation to seabed effects and changes in topography, which are different for intertidal versus subtidal cultivation, due in large part to the proximity of the structures to the seabed and the water depth. The effects of the farm structures on currents and shading would also vary depending on the type of structures used (see Figure 22). The magnitude, spatial extent and duration of effects arising from the spread of pest species and/or disease is considered high for all cultured non-finfish species; however, the pests and/or diseases involved are likely specific to the type of cultivation method and species. As discussed in Section 4.3.4, the farming of organisms such as crayfish and paua that require the addition of food to the marine environment would potentially lead to differences in the effects on the seabed and water column. For instance, the effects of finfish farming, which involves addition of large amounts of feed, can result in more pronounced seabed effects than those associated with oyster or mussel farming, which has less of an enrichment effect on the benthos, but potentially a greater effect on the water column through seston depletion. Farming of macroalgae or deposit feeders such as sea cucumbers would be expected to pose less risk to the environment than the cultivation of shellfish. If co-cultured with shellfish or finfish, they could assist in mitigating adverse effects on the seabed and water column.

While the notion of ecological risk tends to imply a negative or adverse effect, there are clearly some ecological effects from farming shellfish that could subjectively be considered as 'beneficial'. Furthermore, when the range of effects is considered as a whole it could be argued that some nominally 'adverse' effects may be compensated to some extent by more 'positive' effects. For example, although natural seabed sediments and benthos may be altered beneath oyster and mussel farms, local biodiversity and production may be enhanced through provision of habitat for fouling. Hence this range of 'beneficial' to 'adverse' effects needs to be balanced against each other when considering aquaculture developments. Even more broadly, we suggest that management responses to farm developments be made in relation to other sources of environmental risk to estuarine systems at a bay-wide or regional scale, so that the effects of aquaculture are placed in context. This approach was recently applied to mussel farm development in New Zealand (Elmetri & Felsing 2006) using a Relative Risk Model approach described by Landis (2004) and Landis & Wiegers (1997). In this approach, the relative risk to predefined endpoints (*e.g.* particular species, populations, habitats) from a number of sources and stressors in addition to oyster cultivation (*e.g.* agricultural land use, urban development, fishing, climate change) could be investigated and assessed. Such methods can be applied in defined regions (*e.g.* estuaries) or across multiple regions, providing a basis for developing plans for research and prioritising management according to the greatest sources of risk.

6. FUTURE DEVELOPMENTS IN NEW ZEALAND AQUACULTURE

The amount of space designated for aquaculture has expanded dramatically in the past ten years. This is in accordance with the Food and Beverage Taskforce commitment to help the aquaculture sector achieve its goal of $1 billion in sales per annum by 2025. The net result could conceivably be a four-fold increase in farmable space (excluding scallop enhancement areas) over a ten year period, from 4515 ha at the beginning of 2001 to ~20,000 ha by 2011; most of which will be arranged in large individual AMAs. The scale of these sites is such that they are likely to spawn a suite of new innovations and management practices, from on-site farming techniques, to processing and marketing, and with that, conceivably new scale-related environmental effects. The nature of such changes will become apparent over the next five to ten years as these larger AMAs become fully utilised. It is worth noting however, that many of the large AMAs are restricted to staged development, with the progression between stages being dependent on there being no adverse environmental effects.

In terms of the major existing grow-out systems, technologies for mussels are well established and unlikely to change dramatically in the near future. Within the Pacific oyster industry, there is currently a shift away from traditional stick grow-out towards bag or basket grow-out systems (*e.g.* BST grow-out system). While these systems require a higher capital investment, they produce a higher value product and enable greater control over the grow-out process. It is likely that within the next five years, there will be a further development with systems developed for integrating Pacific oyster culture with existing mussel long-line technology. The high value of Pacific oysters (compared with mussels) provides the incentive for this species substitution.

A key development within the mussel industry over the next five years is likely to revolve around access to hatchery spat. This will remove the reliance on existing wild spat catch, potentially reduce the proportion of farm area required for spat management, give better control of harvest timing, and allow the deployment of selectively bred mussels. Selective breeding is likely to focus initially on increasing productivity (with both faster growing mussels and mussels that utilise available food resources more efficiently), but a shift to adding value is likely to occur as suitable traits for improvement are identified. This has been the case with Pacific oyster breeding in New Zealand, where sufficient growth rate gains have been achieved and the focus has shifted to improving product quality. With increased dependency on hatchery spat comes increased potential for genetic issues and this will need to be considered carefully as the industry develops.

The integration of Pacific oysters with mussel farming operations is symptomatic of a general interest in growing new high value shellfish species using the existing farming infrastructure. Cawthron is working with Aquaculture New Zealand to identify and domesticate suitable species for development as emerging aquaculture species. Potential candidates include the flat (Bluff or Tasman Bay) oyster and scallop. Both are high-value filter-feeding species (like mussels and Pacific oysters) where the technical barriers to domestication are likely to be resolved within a 5-10 year horizon. With sufficient market pull, the large-scale production of these species could be achieved relatively quickly without requiring significant capital investment, by integrating with existing production infrastructure.

Research and/or growth trials are being carried out with a number of other marine species including scallops (*P. novaezelandiae*), sea cucumber (*Stichopus mollis*), various macroalgae, rock lobster (*Jasus edwardsii*), sponges, and seahorses. It is possible that some of these species will be produced in commercial quantities within a five to ten year time frame, however, they are likely to remain minor species (in terms of biomass at least) for some time. Although not considered within this report, several finfish species (such as groper, kingfish, snapper and green bone) are also reportedly close to commercialisation and indeed finfish farming is likely to become an increasingly important aquaculture sector. The implications of culturing more than one of these species within the same farm area are discussed in Section 6.1.2.

6.1.1. Offshore aquaculture

As described above, much of the new aquaculture space that has been created in New Zealand is situated offshore, away from the protection of land and in generally more challenging environments. While moving offshore is viewed as a compromise by some in the industry, it has facilitated the desired expansion, and now represents the new frontier of marine aquaculture. Feasibility and optimum utilisation of this space is presently being determined as part of a Government FRST-funded research project (CAWX0302) based around the Hawke Bay open-ocean site. As part of this research, New Zealand's first commercial offshore line has been installed and maintained for ~3 years, and a range of different shellfish species have been trialled with some positive results.

From an environmental perspective, the open ocean represents a much larger system with greater resilience to effects and the necessary spatial scope to de-intensify some traditional farming practices. Although poorly understood at present, the role waves play in the assimilation, resuspension and dispersal of bio-deposits is likely to be particularly important in terms of benthic and water column impact mitigation. By their very nature, open-ocean sites also tend to be situated over soft-sediment habitats that are traditionally only mildly impacted by mussel farming activities (Section 2.3.5). Indeed, preliminary monitoring results from studies beneath New Zealand's first offshore mussel line have so far described a natural, unaffected benthos (Keeley 2006; Sneddon & Keeley 2007).

Presently however, assessments of environmental issues resulting from full-scale operation is limited to predictions, based on: 1) our understanding of the un-altered offshore environment, 2) experience farming in-shore, 3) a small literature pertaining to other semi-analogous offshore structures (*i.e.* oil platforms and FAD's), and 4) ecological intuition. Potential environmental issues associated with farming finfish offshore were reviewed in this light and evaluated in terms of overall risk in Keeley *et al.* (2007). The main findings that were pertinent to farming of 'other species' offshore, are discussed below.

Figure 23 "Innovator" installing New Zealand's first offshore mussel line at Hawke Bay AMA.

Risk evaluation

Areas of environmental compliance that are considered to pose the most risk in the offshore setting, included: seabed effects, biosecurity, habitat creations and wild fish, escapees and genetic contamination, disease and parasites and effects to marine mammals. Potential for seabed effects ranked high primarily because the knowledge and certainty around the issues is considered high, and although it may be effectively managed by reducing stock densities and feeding rates, this is unlikely to be a commercially viable option; therefore, manageability is limited. This issue mainly applies to farming of species that require additional feeds, such as finfish, crayfish, kina and paua. As described throughout this document, extractive forms of aquaculture (*i.e.* filter-feeding organisms) do not have the same scope for benthic effects, particularly in more dissipative and expansive offshore environments. Biosecurity still ranked highly because 1) the effects are potentially irreversible (Forrest *et al.* 2007), 2) the likelihood of issues arising increase with a large-scale farm, and 3) the control of all possible vectors is impractical (*i.e.* limited manageability). This is particularly pertinent to offshore sites, because they tend to become a focal point for recreational fishers, as has been observed at Hawke Bay and Opotiki (N Keeley, pers. obs.). However, most recreational vessels are trailerable and therefore less prone to fouling issues. It is also possible that the spatial isolation of offshore sites removes them from inshore propagation pressure, but the extent to which this occurs is unclear and the subject of on-going FRST funded research.

Genetic effects from escapees were ranked highly for finfish culture species that are endemic to the area, due to the added difficulties of maintaining cage integrity. While this may apply to other mobile species, such as crayfish, it does not necessarily follow for sessile organisms such as mussels. Also of importance here are factors such as the distance of the farm from viable habitat and the dispersal range of gametes from the species concerned; hence it is very much a species-specific issue. The same is true for the management of disease and parasites. Habitat alteration and the associated effects to wild fish populations represents a reasonable risk because farm structures will inevitably be colonised by communities that are not otherwise found in an offshore environment (*i.e.* deep, featureless mud bottom). The effects that this new habitat, in conjunction with an additional artificial food source, may have on wild fish could be important. However, the possible 'severity' of effects was considered low because most wild fish populations are more likely to be 'positively', rather than detrimentally affected. As described in Section 2.5.2, there remains a reasonable degree of uncertainty around this issue.

In terms of risks to marine mammals, the difficulties associated with ranking them using this kind of framework (as discussed in section 5.2) also apply for the offshore setting. Nevertheless, in our assessment, risks to marine mammals from offshore aquaculture are slightly greater than for inshore sites due to the increased likelihood that the activity may be situated near to, or within, important marine mammal habitat. It is also worth noting however, that threats to marine mammals mainly arise from loose ropes (section 2.5.4) and therefore, may be minimised through implementing appropriate 'best management practices'.

Issues that were considered to pose a lower environmental risk include: effects to localised primary production, chemical contamination, effects to seabirds, harmful algal bloom incidence and magnitude and dissolved oxygen depletion. Primary production, or eutrophication, effects were assessed to be the most important of these five, primarily because of the scope for flow-on ecosystem effects. The latter four of these issues scored low in terms of both likelihood of occurrence and potential for negative environmental consequence. Effects to seabirds were interesting in this regard, as it was considered very relevant to offshore sites with the potential to significantly alter bird distributions. However, bird numbers were considered more likely to increase than decrease in farmed locations and the associated consequences were minimal (Keeley *et al.* 2007).

Conclusion

New Zealand and indeed, the world, are yet to experience a fully operational mussel farm of the scale that is planned for some of the existing offshore sites. While many environmental indicators point towards an increased resilience to typical enrichment-related effects, it is also conceivable that new scale-related issues will arise. For example, the cumulative effect of a vast area of structures on hydrodynamics and associated biological processes is difficult to predict and remains undetermined (Goodwin *et al.* 2008; Stevens *et al.* 2008). Economics will inevitably dictate that even large spaces are optimally utilised, which means one or more forms of carrying capacity (see Section 2.4.4) may eventually be reached. Hence, the need for staged development coupled with careful monitoring and pre-established adaptive management responses. There may also be scale-related thresholds that influence the establishment, development and subsequent composition of fouling organisms that will only be realised through experience. It is also conceivable however, that some of the effects will be positive, such as increased abundances of wild fish from the creation of complex pseudo-reef habitat and the likely alleviation of exploitation pressure on commercial fish species. Moreover, larger AMAs (*e.g.* >500 ha) may provide the necessary space for designing functional integrated aquaculture systems, which have the potential to mitigate adverse effects from nutrient rich farm wastes (Chopin *et al.* 2001; Xu 2008; see below - Section 6.1.2).

6.1.2. Integrated culture systems

Internationally, developing integrated culture systems (*a.k.a.* 'polyculture' or 'co-culture'), has been touted as an important future direction for optimisation and sustainability of aquaculture. Growing selected organisms, usually of different trophic levels, side by side can provide nutrient bioremediation capability, mutual benefits to the co-cultured organisms, economic diversification by producing other value-added crops and increased profitability per cultivation unit for the industry as a whole (Chopin *et al.* 2001). Although there have been mixed results with experiments worldwide, the positive literature with respect to productivity (Stirling & Okumuş 1995; Kang *et al.* 2003; Zenone & Sarà 2007; Paltzat *et al.* 2008), and impact mitigation (Zhou *et al.* 2006; Slater & Carton 2007; Hayashi *et al.* 2008; Kang *et al.* 2008), is growing. However, much of the work conducted to date remains in the realms of research, and the commercial uptake of systems has been slow due to a number of scale-related uncertainties (see Troell *et al.* 2003). There are also some possible drawbacks to co-culture of different species. For example, some studies have identified that mussels can act as reservoirs of bacteria pathogenic to fish (Stirling & Okumuş 1995; Kitamura *et al.* 2007; see Appendix 2). The relevance of this issue to New Zealand species is discussed in the respective disease section of this report (*i.e.* 2.5.6, 3.5.6, Appendix 2), but in most instances, remains largely undetermined. In addition, although not quantitatively assessed, combinations of different organisms and associated structures has the potential to create flow impedance issues, thereby affecting flushing rates and related environmental issues.

The potential combinations of New Zealand species are many and varied. Combinations with particular scope for mitigation of environmental effects include: growing sea cucumbers beneath shellfish farms to process deposited organic material (Slater & Carton 2007; Paltzat *et al.* 2008), culturing shellfish around finfish farms to intercept organic particulates and dissolved nutrients (Jones & Iwama 1991, Stirling & Okumuş 1995; Lefebvre *et al.* 2000; La Rosa 2002; Cheshuck *et al.* 2003), the use of algae around fish and conceivably paua/crayfish/kina farms to utilise excess dissolved nutrients (Chopin *et al.* 2001; Kang *et al.* 2003; Zhou *et al.* 2006; Langdon *et al.* 2004; Xu *et al.* 2008; Hayashi *et al.* 2008; Kang *et al.* 2008). Although seeming effective for mitigation, the added complexity inherent in co-culture systems means that they are not necessarily commercially practical or economically feasible. There also remains the trade-off between possible benefits co-culture systems and the likely physical draw-back of compromising flushing. They are therefore unlikely to be widely adopted in the near future unless necessitated by compliance with environmental legislation or market demands change. In the case of shellfish farming in New Zealand, environmental effects are relatively minor and the evolution of co-culture is more likely to be driven by production and market diversity incentives - which remain less well proven. However, there remains considerable scope for innovative co-culture in conjunction with fish farming (or other food-added forms, *e.g.* paua, crayfish), where significant enrichment problems can occur

(Forrest *et al.* 2007). There are also signs of a general shift in farming philosophy, toward placing a greater emphasis on sustainability and optimal use of resources, and to this end, co-culture may play a pivotal role.

7. MANAGEMENT AND MITIGATION OF ECOLOGICAL EFFECTS

7.1. Site selection

Our review highlights that the nature and magnitude of effects largely depend on site-specific conditions relating to the intensity of farming, flushing characteristics of the environment, and the proximity of the farm to valued habitats (*e.g.* rocky reefs) and species (*e.g.* nesting shorebirds). Effects to the seabed may be reduced by locating farms in high current environments or open coastal situations in sufficient depths such that increased currents and wave action enhances dispersion of farm-generated wastes over a wider area. Tools such as predictive depositional models (DEPOMOD; Cromey *et al.* 2000) can be useful in estimating the spatial extent and magnitude of effects prior to new developments. Monitoring data suggests that diffuse organic loading beyond the immediate deposition footprint can be effectively assimilated into the receiving environment and may in fact result in a slight increase in productivity in the sediments (Forrest *et al.* 2007). Wider ecological effects on marine mammals and seabirds can be effectively mitigated through properly placing farms in locations that are well removed from critical breeding and foraging areas.

A shift towards high-flow sites does, however, increase the likelihood that farms are situated within close proximity to traditionally ‘higher value’ communities. The physical properties of high flow sites tend to coincide with non-depositional reef substrates and coarser, well-flushed sediments (*e.g.* gravel, sand, and shell) that are colonised by diverse and complex reef communities facilitated by the strong currents and good food supply. This is particularly relevant in the placement of food-added culture systems, which require particularly high flows to dissipate waste. Hence, the traditional philosophy of placing marine farms in depositional basins is increasingly being challenged. At present enrichment-related effects on reef biota are relatively poorly documented (Keeley *et al.* 2008). Offshore sites may provide the best of both worlds in this regard, as they are often situated in strong current flows, have the added but undefined dispersive contribution of wave action, and are some distance from coastal reef fringes.

7.2. Farm management

Shellfish farmers have adopted an environmental code of practice (ECOP) for managing inputs of debris associated with the development and maintenance of farm structures. Entanglement risks for marine mammals can be minimised by adopting measures such as keeping lines taut, using thicker lines when possible (Kemper *et al.* 2003), and ensuring that farms are well maintained (*e.g.* removal of broken or loose crop lines). These types of design and maintenance features, and operational procedures for lines that minimise entanglement risk, have already been implemented at New Zealand shellfish farms as part of the ECOP.

Seabed effects from individual farms can be managed through the development of environmental criteria and maintaining an appropriate stocking density, which can be integrated into adaptive management plans (AMPs), as has been the approach with salmon farming in the Marlborough Sounds (Forrest *et al.* 2007). Monitoring of environmental effects coupled with either staged or adaptive management is a useful approach in situations where there are uncertainties regarding environmental effects due to either the scale of the development or the proximity to habitats of high perceived ecological value or susceptibility to depositional effects. Seabed enrichment effects from feed-added forms of aquaculture can also be mitigated y using single-point mooring systems, which spread the discharge of a greater area (Goudy *et al.* 2001).

7.3. Integrated culture

Integrated culture involves the cultivation of two or more species, usually of different trophic levels, in close proximity to one another. It is a rapidly advancing area of research and has considerable scope for mitigation of environmental effects in the future. Uptake by industry is presently constrained by environmental necessity and/or proven economic incentives. See Section 6.1.2 for more details.

7.4. Addressing biosecurity risks and managing pest species

The adverse effects of pest introduction and spread, that can have profound non-local and irreversible consequences, are arguably more significant than the commonly cited seabed effects. Clearly, there is a need to redress the balance of effort in future studies. This could include, for example, site-specific risk profiling for actual and potential pests (*e.g.* assessment of the likelihood that high risk species will establish), estimation of the significance of pest spread by marine farming pathways relative to other sources of risk (*e.g.* recreational vessels), and consideration of the feasibility of management.

In recognition of biosecurity risks from aquaculture operations, regional councils are increasingly stipulating conditions on resource consents that require management of biosecurity risk in some form. Unfortunately, some councils have prescribed conditions that are either ineffective (will not lead to biosecurity benefits because significant risks already exist) or for which compliance (or evaluating compliance) is not feasible. In part, this situation may reflect a lack of knowledge and experience with marine biosecurity issues, and is a problem that should ideally be addressed at a national level so that pragmatic consent requirements are achieved and applied consistently among councils.

Irrespective of regulatory requirements, aquaculture companies tend to be pro-active in developing biosecurity management strategies, as they clearly have a strong incentive to protect their operations from the adverse effects of pest species. Among other things, within the mussel and Pacific oyster industries the various strategies have included development of Biosecurity Management Plans, Codes of Practice for seed-stock transfers, and related methods to manage biofouling (*e.g.* NZMIC 2001; Taylor *et al.* 2005). Additional ways in which aquaculture companies can contribute to the effective management of biosecurity risks were discussed by Forrest (2007).

There are also a range of emerging tools, methods and knowledge from studies in New Zealand and elsewhere that can assist the industry in their management approaches (Forrest & Blakemore 2006; Forrest *et al.* 2006; Coutts & Forrest 2007; Pannell & Coutts 2007; Piola *et al.* 2008). Although the characteristics of pest species and their environments often limit 'manageability', it is also important to recognise that management success can to a large extent hinge 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 of key stakeholders at a regional and national level; failure to eradicate *Didemnum* from the Marlborough Sounds (an undertaking considered by Coutts & Forrest 2007 to be technically feasible) is a case in point.

7.5. Disease

A number of diseases documented overseas would have significant impact on the New Zealand aquaculture industry if they were to become established here (Appendix 2). In some cases they also have the potential to impact on wild conspecifics and conceivably associated fisheries. Good biosecurity practices and surveillance as described above are probably the best ways of managing the threat. Specific mitigation factors should be devised from best practice elsewhere should one of these exotic diseases become established.

7.6. Managing genetic diversity

A common thread running through this report is that managing genetic diversity of wild, indigenous conspecifics is an important environmental consideration. In most existing forms of aquaculture this risk is already mitigated to a large extent due to stocks being sourced from inherently genetically diverse wild populations (*e.g.* mussels), or by the species being non-indigenous (*i.e.* in the case of Pacific oysters). But there remain risks associated with up-scaling the culture of new species, and/or with increasing dependency on hatchery-reared stock. These risks are manageable through identifying the genetic structuring within the wild population prior to implementation and regulating transfer between regions accordingly, and through careful management of selectively bred stock to ensure adequate genetic diversity. For example, steps can also be taken at the grow-out stage to manage and maintain diversity of farmed stock within farms/bays/regions by setting standards for combinations of families within a bay (or other relevant area based on progeny dispersal range). In some instances, farmers may also adopt triploidy, which theoretically negates genetic contamination issues.

8. REMAINING INFORMATION GAPS

Overall, this review highlights that our present knowledge of ecological effects arising from New Zealand's two most widely practiced forms of aquaculture is reasonably good. This is particularly true for the more 'conventional' effects associated with the seabed, and to a lesser degree, water column processes. It is also apparent that the wealth of information and level of knowledge is high when put in the context of effects associated with other coastal activities (*e.g.* sedimentation and smothering effects from dredging, NZ and species specific toxicity levels, effects of human activities on marine mammals). However, through this review we have identified areas where knowledge is lacking or can be improved. Inevitably many of these gaps are associated with the culturing of 'new species'. Noted information gaps include the following (in no particular order):

- There is limited information on the actual rates of sedimentation occurring beneath and adjacent to marine farms. Such information is necessary to validate models used in predicting depositional footprints and for determining the rates of deposition that can be effectively assimilated by the environment (*e.g.* deposition may be occurring at distances well beyond the farm but are not detectable based on monitoring indicators such as organic enrichment of sediments). Along these lines there is little available information on the links between seabed effects and the water column (*e.g.* the influence of organic enrichment of the seabed on water-column nutrient chemistry).
- There is little known about the effects of aquaculture and associated biodeposits on high value reef communities that can be found in close proximity to some farm areas. In particular there is a paucity of information surrounding how taxa such as sponges, hydroids, ascidians *etc*., as well as mobile reef epibiota (*e.g.* crabs, brittle stars), respond to organic deposits. Some tolerant reef communities are considered useful from an impact amelioration standpoint (Angel & Spanier 2002; Gao *et al.* 2008), while others are likely to be highly enrichment sensitive and it would be useful to know more about how various taxa groups respond. Likewise, effects on adjacent intertidal habitats remain poorly documented.
- This study also identified a notable dearth of information surrounding the effects of marine farms on the wider food web and in particular, wild fish assemblages. Although this has not been a big issue to date, it is apparent that the scope for interactions between commercial fish species (as well as other species including marine mammals) and marine farms will increase with the development of the several new large offshore farms. Scale-related effects from larger farms on habitats and associated ecosystem function are difficult to predict and is likely to be an area of some interest during their development.
- Through water column surveys and application of numerical models, we have a reasonably good understanding of the effects of filter feeding bivalves on seston depletion. However, we know little regarding the effects of bivalve aquaculture on the composition of plankton communities, which in turn may have wider ecological effects on the food web. Included in this information gap is the general lack of research surrounding the potential consumption of larval zooplankton species (e.g. fish, crustaceans) and the subsequent ramifications for their recruitment success.

- Considerable growth in the aquaculture industry as anticipated over the next 15 years (NZAS 2006) will in turn require a better understanding of the wider ecosystem effects of shellfish aquaculture, particularly with regard to the cumulative effects of additional and aquaculture development (along side other anthropogenic stressors) within the context of ecological carrying capacity. Research to address wider ecological issues where information is relatively sparse will require understanding of complex ecosystem processes, many of which occur beyond the immediate environment of the cultivation area (*e.g.* changes to food web pathways). Modelling approaches have been undertaken to evaluate trophic effects from culturing oysters (Leguerrier *et al.* 2004) and mussels (Jiang & Gibbs 2005) and further development of these types of models may assist in forecasting cumulative ecosystem-scale effects.
- The relationship between the environment and the growth of the main New Zealand culture species, which underpins any related ecosystem models, is presently poorly defined. A better understanding of the feeding physiology and energetics of New Zealand's main aquaculture species would greatly improve confidence and reduce variance in model outputs, particularly when it comes making predictions for new environments (*e.g.* offshore).
- In Section 7.4 we highlighted a need for better understanding of biosecurity threats. For example, disease outbreaks and transmission from cultured shellfish, while not currently identified as a major issue, does carry with it a high level of risk. Hence we need to understand more about how increasing aquaculture, or perhaps diversifying cultured species, may in turn increase this risk on the New Zealand environment. A useful step would be to gauge the susceptibility of cultured species by assessing novel disease loads in the same organism growing in foreign waters. Other important information needs that would allow better assessment of disease risk include identification of APX (see Appendix 2) to species level and differentiating it (or otherwise) from the APX in flat oysters. Also, life-cycle studies on *Marteilia* to ascertain the stringency of intermediate host specificity.
- Present stock management practices for Greenshell™ mussels do not appear to pose a significant threat to the genetic diversity of wild mussels. However, this is partly afforded through the genetic diversity that is implicit in wild-sourced spat and has the potential to change with the advent of selectively breeding for farms. It would appear that more research is required into the potential genetic implications of this practice, leading to the development of sensible brood-stock management and farming protocols.
- Pacific oysters have been reported to show no evidence of reduced genetic variation (Smith *et al.* 1986). This lack of a founder effect is surprising, but on the positive side it would suggest that the naturally high resistance of this species to many infections has not been degraded by genetic bottlenecks in New Zealand populations. Further research is required to confirm this. Such work would also be an opportunity to ascertain gene flow between naturalised and cultivated New Zealand *C. gigas*. This might also afford insights into potential pathogen flows between populations.