An overview of factors affecting the carrying capacity of coastal embayments for mussel culture

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Executive Summary

The process of determining an environmental carrying capacity for any activity involves two elements: (1) a description of the relationships between levels of the activity and their environmental effects, and (2) a critical assessment of the desirability of the environmental effects. This report reviews the state of knowledge in applying the carrying capacity concept to the development of shellfish aquaculture in New Zealand's coastal waters. The report describes:

- Factors affecting carrying capacity for mussel farming,
- Environmental influences on variations in carrying capacity,
- Environmental and ecosystem effects that may be encountered in an area as the number of mussel farms increases, and
- Numerical models developed by NIWA to simulate factors affecting shellfish production at different stocking densities.

Four generic types of carrying capacity can be applied to coastal aquaculture development:
- *physical carrying capacity* – the total area of marine farms that can be accommodated in the available physical space,
- *production carrying capacity* – the stocking density of bivalves at which harvests are maximised,
- *ecological carrying capacity* – the stocking or farm density which causes unacceptable ecological impacts,
- *social carrying capacity* – the level of farm development that causes unacceptable social impacts.

Physical constraints to the number and size of farms that can be located in an area are provided by the geography of the waterway, the requirements for farm development, and existing planning restrictions. The amount of phytoplankton production and its rate of supply to farmed areas by natural water movement usually limit the total biomass of bivalves that an area can support (i.e. "production capacity"). Models developed to estimate production carrying capacity simulate environmental processes that determine the supply of phytoplankton to culture areas and the rate at which this food is converted to productive tissue. *Ecosystem models* simulate these processes over broad scales that encompass the cultivation area. They generally include interactions between the culture system and a range of physical and biological processes that affect the transfer of organic material among different benthic and pelagic components of the ecosystem. *Local-scale production models*, on the other hand, are developed predominantly to assist site selection and the optimisation of stocking density at a particular location.

Production models developed by NIWA extend earlier ecosystem models by simulating the effects that bivalve populations have on their food supply through the recycling of water-column nutrients. The overall model incorporates: (1) a *hydrodynamics model* that simulates the effects of tides, freshwater inputs and weather on current flows, flushing rates and water column structure, (2) an *ecosystem model* that simulates the effects of light, water stratification and nutrients on the distribution and abundance of phytoplankton and zooplankton, and (3) a *mussel energetics model* which simulates the growth and condition of mussels under different food conditions.

Simulations have shown that the vertical stability of the water column is a major factor controlling the supply of light and nutrients to phytoplankton in the Marlborough Sounds. Year-to-year variability in phytoplankton abundance in Pelorus Sound has been linked to variability in the stratification of the water and freshwater inflows. This variability has consequences for the growth and condition of bivalves. Although the Greenshell^{TM} mussel, *Perna canaliculus,* is able to adjust its feeding rates over a wide range of plankton concentration, growth drops off quickly and becomes negative once concentrations of phytoplankton drop to between 1.0 and 0.5 μg/litre of chlorophyll (an indicator of phytoplankton abundance). Extended periods of low phytoplankton productivity, caused by a breakdown in water stratification, result in a net loss of nutrients from the system and may have persistent effects on primary production and mussel growth in subsequent years.

Studies of the ecological and social impacts of mussel culture have been limited to descriptive accounts of the environments of relatively small (~3 – 5 ha.), single, established farms. Direct ecological effects of the farms are relatively minor and, with good management, can be restricted to the immediate footprint of the farm. The effects include organic enrichment of sediments by mussel faeces and pseudofaeces, shading of benthic habitats, deposition of shells and other farm debris and localised depletion of phytoplankton. There is, however, a critical lack of strategic information on the environmental changes that might occur with increases in stocking density, farm size and farm number. Potential diffuse and cumulative effects of shellfish culture could include shifts in primary production within sheltered embayments, changes in predator behaviour and abundance, off-farm effects on natural assemblages and changes in the abundance and distribution of "problem" species. Potential social impacts include displacement of other stakeholders, decreased satisfaction and enjoyment of other users, changes in visual amenity and natural character, and diminution of future opportunities.

Understanding and measuring these effects, if they do occur, will require a commitment to strategic, regional-scale assessment and modelling during the course of any future industry development. Several approaches are recommended:

- Development and testing of indicators of regional ecosystem condition
- Adaptive monitoring of new farm developments and appropriate reference areas to characterise the effects of novel types and sizes of farms in new environments.
- Sampling and experiments along a gradient of intensity of existing marine farm development to determine differences among embayments subject to different levels of marine farming,
- Comparison with reference areas that remain unaffected by marine farms,
- Use of archival information to reconstruct historical baselines for natural assemblages in farmed embayments,
- Analytical surveys and focus-groups of other stakeholders to develop methods for predicting and assessing social and cultural effects of marine farm development.

1   INTRODUCTION

Marine farming is currently experiencing rapid growth in New Zealand. Much of this is attributable to production of Greenshell™ mussels, *Perna canaliculus*. In the last 4 years alone, mussel production has almost doubled to over 70, 000 tonnes.yr^{-1} (Jeffs *et al.* 1999). Industry sources predict a further trebling of demand over the next decade and continuing growth of the industry (New Zealand Mussel Industry Council 1998).

Around 2,500 ha. of coastal seabed are currently allocated to mussel production throughout the country (Jeffs *et al.* 1999). The growing market for Greenshell™ mussels has meant that there is increasing demand to set aside further areas of coastal seabed for marine farm use. Resource consent applications for new mussel farms cover another 8000 ha. of seabed (MacKay 2000). Many of these proposals are for farms that are more than two orders of magnitude larger than most existing holdings and concerns have been raised about the ability of coastal environments to support further substantial increases in shellfish production.

This report provides an overview of the application of the carrying capacity concept to marine farm development in coastal embayments. Detailed numerical models have been developed in a number of countries to predict the biomass of bivalves that can be supported by particular coastal ecosystems (i.e. their "carrying capacity"). The report draws upon this literature and research done by NIWA on the New Zealand mussel industry to describe the application of carrying capacity models to the management of coastal inlets and estuaries subject to mussel culture. In particular, the objectives of the report are:

- To outline the factors affecting the carrying capacity of coastal embayments for mussel farming and likely variations in carrying capacity,

- To review the carrying capacity models developed by NIWA,

- To review the ecosystem effects that may be encountered in an area as the number of mussel farms increases, and

- To outline the current level of understanding of the carrying capacity of New Zealand coastal waters for aquaculture.

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2 MUSSELS AND MUSSEL CULTURE IN NEW ZEALAND

Several species of mussel (bivalves in the family Mytilidae) are present in New Zealand. Two of these – the greenshell mussel, *Perna canaliculus*, and the blue mussel, *Mytilus galloprovincialis* – are collected for consumption. Blue mussels occur predominantly in the mid- intertidal zone of rocky shores. Although they and related species of *Mytilus* (predominantly *M. edulis*) are cultured in other parts of the world, the New Zealand mussel industry has specialised in farming the endemic greenshell mussel. *P. canaliculus* is predominantly a sub-tidal species that occurs low on rocky shores and in clumps on the sandy and muddy bottoms of sheltered embayments. It is able to tolerate a broad range of water salinities and temperatures and occurs in a wide variety of coastal habitats throughout New Zealand (Jeffs *et al.* 1999).

A recent study by Gardner (2000) speculated that the absence of *P. canaliculus* and other mussels from exposed shores in Cook Strait is attributable to low concentrations of planktonic food in the surrounding waters. This study did not, however, consider the broad range of other physical and biological processes that act to determine the natural distribution of mussel populations on rocky shorelines in New Zealand. For example, Menge *et al.* (1999) have shown that mussels are absent from many rocky shorelines on New Zealand's west coast, despite generally greater recruitment of mussel spat than to east coast shorelines. Predation by seastars (*Stichaster australis*) and interactions with grazing limpets appear to play important roles in determining this pattern of distribution.

Mussel farming is a relatively non-intensive form of aquaculture that relies upon natural environmental processes for the provision of seed stock and food. In New Zealand, farms use a longline culture system in which the mussels are grown on ropes ("droppers") suspended in the water column from groups of long, buoyed lines ("longlines"). The ropes are seeded with mussel spat that are obtained either from direct settlement onto fibrous collecting ropes (~20% of all spat for farms throughout New Zealand), or which are collected on macroalgae that wash up on Ninety Mile Beach (~80% of spat).

Mussels feed on phytoplankton, detritus and other organic particles which they filter from the water column. They are very efficient at removing particles in the size-range 3-200 μm. Only a proportion of the filtered material is ingested, however. The rest is expelled as mucous bound deposits of organic and inorganic material (pseudofaeces) which settle on the seafloor below the farms. The marketable size for *P. canaliculus* is around 100 mm length. Growth rates of mussels can vary substantially among different localities and years. Most of this variation is associated with variability in phytoplankton abundance (Hayden 1995).

3   THE CARRYING CAPACITY CONCEPT

At its most basic level, the concept of carrying capacity describes the relationship between the size of a population and change in the resources on which it depends. It assumes that there is an optimal population size that can be supported by the resource. The concept was originally applied to rangeland management where it was used to describe the maximum stocking rates that could be achieved on pastures before there was noticeable deterioration in the quality of the pasture or the stock (Odum 1959). This relatively simple concept has since been used in a broad range of resource management contexts, from wildlife management in national parks to optimising recreational experiences in natural environments (Shelby and Heberlein 1986).

The utility of the carrying capacity concept is contingent upon there being clear objectives to be achieved in the condition of the population or the resource. Although it is not often acknowledged explicitly, the process of determining an environmental carrying capacity for any activity requires a value judgement about what is to be optimised. For example, in considering the relationship between grazing herbivores and plant populations, Caughley (1979) distinguished between two types of carrying capacity: the "ecological capacity" and the "economic capacity". The former describes the size of the herbivore and plant populations that would be reached naturally if they were allowed to interact without human intervention. The latter describes an equilibrium that is imposed by sustainable harvesting of the herbivore population. In this instance, the objective is to optimise the harvest of herbivores, potentially keeping them at smaller densities than might be achieved naturally. Different management objectives may, therefore, imply different optimal population sizes. The process of establishing the environmental carrying capacity for any activity involves describing the relationship between levels of the activity (in this case mussel farming) and its environmental effects, and a critical assessment of the desirability of different environmental effects under alternate management regimes. For the concept to be applied usefully to manage natural resources there must be agreement about which elements of this interaction are to be optimised.

For the purposes of this review, we have defined four generic types of carrying capacity that are relevant to the management of coastal aquaculture (Table 1). The *physical carrying capacity* of an area relates to the size and number of farms that can be accommodated in the physical space that is available. Limits to this space are set by the physical geography of the area, planning restrictions (e.g. requirements for navigation or zoned areas in coastal resource plans) and the requirements for farm development (e.g. water depth, proximity to handling facilities, etc). *Production carrying capacity* refers to the stocking density that allows the sustainable harvest of bivalves to be maximised. Here, the focus is on determining the optimum long-term harvest of bivalves that an area will support. Effects on other components of the

ecosystem are considered only in so far as they have the potential to affect bivalve production. This differs from the *ecological carrying capacity* of an area where the main management concern is the effects that stocking or farm density have on the surrounding ecosystem. The ecological carrying capacity can be described as the level of farm development beyond which ecological impacts of farming become unacceptable. A similar definition can be applied to the *social carrying capacity* of an area with regard to social impacts, such as effects on visual amenity or displacement of other activities.

TABLE 1. *Four types of carrying capacity that may be applied to aquaculture development and the spatial scales at which they are most relevant.*

	Definition	Likely scale of effect
Physical carrying capacity	Limits set by the physical space and conditions required for marine farms (size, situation, water depth, etc)	Subembayment→Planning area
Production carrying capacity	The sustainable stocking density at which production levels are maximised	Farm → embayment → adjacent embayments → region
Ecological carrying capacity	Levels at which farm development causes significant changes in the ecosystem	Farm→embayment→region
Social carrying capacity	Levels at which farm development impairs or conflicts with other human use	Embayment→region

Most published work on the carrying capacity of coastal ecosystems for shellfish aquaculture has focussed on the problems of determining the production capacity of sheltered waters and the ecological impacts of marine farms. NIWA's multidisciplinary research programme is investigating elements of each type of carrying capacity, but most work to date has been centred on issues affecting production and ecology capacities. For these reasons, the review will focus mostly on these two areas.

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3.1   Physical carrying capacity

Sites for growing *P. canaliculus* require shelter from severe waves and wind, high water quality, depths of > 5m and good water flow (Jeffs *et al.* 1999). The availability of these conditions within embayments places limits on the number and size of farms that can be developed. Other major constraints are provided by a variety of existing spatial planning mechanisms. These include restrictions placed by local government coastal resource plans, DoC guidelines (DoC 1995) – which recommend development away from specified habitats of ecological importance –, identified areas of importance for wild-fisheries, marine protected areas and navigational concerns (Anon. 1995, Hickman 1997). For example, until recently, farm development within the Marlborough Sounds has been mostly within 200 m of the shoreline, predominantly for reasons of navigation, so that the centres of the bays were kept clear for other users. Recent applications for farms beyond the 200m mark reflect the fact that, in most embayments, there is limited space remaining for farm development close to the foreshore (De Zylva 1996).

Questions about the physical capacity of embayments for marine farms are the most tractable of the four forms of carrying capacity. They require information on the environmental conditions needed for siting marine farms to be incorporated into geographical planning frameworks (e.g. GIS). These frameworks should also identify spatial constraints to farm development provided by the physical landscape and other planning considerations.

3.2   Production carrying capacity

Carrying capacity models for bivalve production are concerned mostly with determining the biomass of bivalves that a farm or waterway can support before growth rates are reduced below an acceptable target level, or before mortality increases beyond acceptable limits (Carver and Mallet 1990, Dame and Prins 1998, Smaal *et al.* 1998, Ross and James, unpubl. manuscr). In general, these "targets" are set by commercial considerations, such as the time required to grow to a marketable size (Smaal *et al.* 1998, Ross and James, unpubl. manuscr.).

Production models have been developed to support management of bivalve culture in Ireland (Rodhouse and Roden 1987, Ferreira *et al.* 1997), Canada (Mallet and Carver 1990), France (Bacher *et al.* 1997), the Netherlands (Van der Tol and Scholten 1997) and South Africa (Monterio *et al.* 1998). The way in which each model has been developed varies according to the purpose of the study, the species involved, and the extent of existing information. For example, carrying capacity models for the Marennes-Oléron Bay in France are based on long-term data sets on the population dynamics of cultured bivalves within the bay, predominantly the oyster, *Crassostrea*

gigas. Data on long-term changes in the overall biomass of bivalve stock, growth and mortality schedules of oysters were combined to examine historical conditions under which growth to a harvestable stage was optimised (Héral 1996). More recent production models have been based on the dynamic trophic relationships that determine the growth and condition of bivalves. These describe the main processes that govern fluxes of energy, carbon or nutrients in coastal ecosystems that influence bivalve growth. The main source of change in the growth and condition of bivalves is variability in the rates of ingestion and assimilation of food (Bayne *et al.* 1989). Factors that determine the supply of phytoplankton and other organic material to culture areas and the rates at which this food is taken up and converted to productive tissue are, therefore, at the core of most carrying capacity models.

Production models can also be characterised according to the spatial scale of investigation and the level of detail that is included within the model. For example, the natural supply of food to cultured bivalves can be modelled as the end result of dynamic broad-scale (i.e. system-wide) processes that affect primary and secondary production throughout the study area. These are referred to as *ecosystem production models*. Ecosystem models may include components (submodels) that describe dynamics in nutrient availability (e.g. pathways of carbon and nitrogen transfer), detritus, the population dynamics of bivalves and other grazing competitors (e.g. zooplankton) and the rates of phytoplankton production, consumption and mineralisation that determine the rate of transfer of material between each component of the ecosystem. Large-scale hydrodynamic processes that affect the movement and exchange of water and suspended particles throughout the system are also included.

Local-scale production models, on the other hand, are developed predominantly to assist site selection and the optimisation of stocking density within a farm (Smaal *et al.* 1998). They describe hydrodynamic transport processes (e.g. current velocities and profiles) within the immediate vicinity of the farm, bivalve growth and physiology (often as a function of local stocking density) and elements of farm management.

The processes that determine the rate of production and distribution of phytoplankton are highly dynamic across a range of spatial and temporal scales. Choice of a particular scale of investigation, therefore, necessitates trade-offs between the complexity of processes that can be simulated as part of the model and the spatial resolution of the model. This means that local-scale models tend to have more detail on fine-scale hydrodynamic processes, but treat ecosystem processes, such as the effects of nutrient availability on primary production, as inputs and outputs from the small-scale system. Ecosystem models contain only limited spatial resolution (i.e. they assume homogeneity in the environment over larger areas), but include interactions between a range of processes that affect mussel growth and survival within an

embayment. The choice of scale and model type is, therefore, determined by the types of management questions that the model is intended to address.

3.2.1 Feedback mechanisms (ecosystem effects on trophic exchange)

An important limitation of most existing models of production carrying capacity is inadequate information on the feedback mechanisms between bivalve culture and ecosystem processes. An example of an important feedback mechanism is that of the nutrient cycle in which particulate nitrogen is removed from the water by phytoplankton which are in turn consumed by the shellfish. Dissolved nitrogen is then released by the shellfish as ammonia which is preferentially taken up by phytoplankton. In natural systems, the amount of phytoplankton production limits the total biomass of bivalves that may be supported. Large increases in the density of bivalves may potentially change patterns of nutrient distribution and recycling within an embayment that affect overall primary production. Although there is no direct addition of organic matter to the ecosystem, mussels concentrate organic material by processing phytoplankton into faeces and pseudofaeces. Deposits produced by the blue mussel *Mytilus edulis*, for example, contain between 13-15% organic carbon and 1-1.2 % organic N by weight (Dahlbäck and Gunnarsson 1981). Estimates suggest that about 33% of the nutrients ingested by the mussels is deposited on the seafloor (Folke and Kautsky 1989). A further 25% of what is ingested is removed as mussel tissue during the harvest. This can mean that formerly dispersed nutrients and organic matter are increasingly concentrated in areas subject to intensive mussel culture.

Large densities of mussels can also reduce zooplankton densities through direct predation, or indirectly, through competition for food (Horsted *et al.* 1988). Grazing by zooplankton often removes a large proportion of annual phytoplankton production within an embayment (e.g. 29%, Rodhouse and Roden 1987). At very high stocking densities, the combined effects of intensive predation by mussels on zooplankton and faster recycling of nutrients could result in significant shifts in the quality and availability of phytoplankton that, in turn, affect mussel growth. Importantly, phytoplankton is also a major food source for other natural and cultured populations of bivalves, such as scallops, clams and oysters so that any changes in the quality and quantity of this food may have flow-on effects to other harvestable resources in an embayment. Few studies have modelled the stocking densities at which such shifts in system function might take place.

3.3 Ecological carrying capacity

A growing number of studies have examined the direct effects of mussel culture on surrounding environments. These have almost invariably been simple, descriptive

accounts of ecological differences between established culture sites and comparable areas away from the farms. There have been no attempts to incorporate a more analytical sampling framework that might provide information on the relationships between the intensity of farm development or stocking levels and the severity of ecological changes. Similarly, few studies have documented the temporal patterns of change in ecological assemblages as farms have been developed. Surveys of established culture sites have, however, shown that some adverse effects of mussel culture are possible. These include:

- organic enrichment of sediments below the farmed areas by faeces and pseudofaeces,

- shifts in benthic food webs from predominantly suspension-feeding to deposit-feeding faunas,

- shading of submerged plants and animals by surface infrastructure,

- drop of shells and other waste materials,

- localised depletion of phytoplankton from surface and sub-surface waters, and

- attraction of predators, such as starfish and fish (Cole and Grange 1996, Kaiser *et al.* 1998, Stenton-Dozey *et al.* 1999, Cole *et al.* in press).

The severity of these environmental effects and their ecological significance varies with the size and configuration of the farm, the type of activity undertaken at it (i.e. grow-out or spat collection), prevailing environmental conditions, and the specific conservation values of the lease site. They are not present at all farm locations and generally the effects are limited to the immediate vicinity of existing farms.

3.3.1   Organic enrichment of sediments

Rates of particle sedimentation beneath mussel farms are often 2 to 3 times greater than at comparable locations away from the culture areas. Measured rates of sedimentation at farm sites range from around 3 $g.m^{-2}.d^{-1}$ to as high as 945 $g.m^{-2}.d^{-1}$ (Table 2). Many of the direct impacts of mussel farming are associated with the deposition of this material – which has a high organic content – on habitats beneath the culture area. The rate of sedimentation and the associated ecological effects vary seasonally with phytoplankton abundance and seston quality, but are also related to farm size, stocking density and the hydrodynamic environment of the farm. Measurements taken by NIWA under mussel farms in Beatrix Bay, Pelorus Sound ranged from 5 to 107 $g.m^{-2}.d^{-1}$. The upper end of this range represents measurements taken following storms or harvesting, when accumulated deposits were dislodged from the mussels and culture lines. This rate is, however, still at least an order of magnitude lower than rates of sedimentation under salmonid cages, which can regularly average

up to 20 times ambient levels (Folke and Kautsky 1989, Morrisey *et al.* unpubl. manuscript). Unlike salmonid culture, where food pellets and faeces account for large quantities of the sedimented organic material, particles deposited beneath mussel lines consist predominantly of faeces and pseudofaeces produced by mussels feeding on natural sources of organic material.

At consistently high rates of sedimentation, organic enrichment of sediments by mussel faeces and pseudofaeces can cause increases in the rates of respiration and oxygen consumption by benthic microorganisms. In well-oxygenated sediments, where there is good water movement, full degradation of biodeposits occurs quite rapidly (within 18 days; Grenz *et al.* 1990). In poorly flushed areas, limited exchange of oxygen within the surface sediments can rapidly lead to anoxic[1] conditions, as the demand for oxygen exceeds the rate of exchange in pore water. In these circumstances, benthic metabolism becomes increasingly anaerobic[2]. Severely affected areas are characterised by films of chemoautotrophic sulphur bacteria (*Beggiatoa*) at the sediment-water interface and black, anoxic sediments (Grant *et al.* 1995). The by-products of anaerobic metabolism, including sulphide (usually in the form of H_2S, produced as a result of anaerobic sulphate reduction) and ammonium (produced by anaerobic and aerobic mineralization of organic matter) build up in the sediments. Overseas studies of mussel (*Mytilus*) culture show that in severely affected farm sediments, sulphide concentrations can be up to 100 times greater than elsewhere (Dahlbäck and Gunnarsson 1981). Most (70 - 90%) of this occurs in the top 14 cm of the sediment (Tenore *et al.* 1982). Ammonium efflux from the sediments can also be an order of magnitude greater below mussel farms than from areas outside the farms (Grant *et al.* 1995). The severity of these effects is likely to be influenced by the extent of primary production in the embayment, the amount of water flow and flushing of the culture area, and the size, stocking level and distribution of farms (Hatcher *et al.* 1994, Grant *et al.* 1995). Residual effects may be detectable up to 3 years after the culture system has been removed (Stenton-Dozey *et al.* 1999).

Few comparable studies have been done of existing New Zealand mussel farms. Kaspar *et al.* (1985) compared sediment conditions at a single farm site (~1.5 ha.) in Kenepuru Sound with a reference location outside the farm. They found that the ammonium pool in sediments beneath the farm was approximately twice that of the reference site and that rates of nitrogen mineralisation were also elevated. There was no evidence of severe anaerobiosis. Interpreting the findings of Kaspar *et al.* (1985) and many other studies of farm impacts is, however, complicated by the lack of appropriate sampling that would allow natural spatial variability in sediment

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[1] Lack of oxygen
[2] Respiration occurs in the absence of oxygen

TABLE 2.   *Rates of sedimentation recorded beneath mussel culture areas in different parts of the world.*

Species	Country	Culture Method	Farm size (ha)	[†]Stocking density	Water depth below farm	Culture depth	Sedimentation Rate $(g.m^{-2}.d^{-1})$	% of Ambient Rate
[1]*Mytilus galloprovinciallis*	South Africa	Raft	80.0	0.18 t.m^{-2}	11	6	945	~ 300
[2]Mytilis edulis	Canada	Long-line	0.4	[‡]400 mussels.m^{-2}	7	3	20 – 170	~ 250
[3]Mytilus edulis	Sweden	Long-line	0.3	0.03 t.m^{-2}	10	n.d.	4	~ 200
[4]Mytilus edulis	Spain	Raft	0.6	0.44 t.m^{-2}	16	8	3	n.d.
[5]Perna canaliculus	New Zealand	Long-line	3.0	0.01 t.m^{-2}	28	10	5 – 107	250 - 1300

References: [1]Stenton-Dozey *et al.* 1999, [2]Hatcher *et al.* 1994, [3]Dahlbäck & Gunnarsson 1981, [4]Tenore *et al.* 1982, [5]unpubl. NIWA data from Beatrix Bay, Pelorus Sound.

[†]Estimated from farm size and harvested biomass.

[‡]No comparable data on biomass were presented

conditions to be distinguished from farm effects. This requires sampling at multiple farm locations and multiple reference locations.

3.3.2   Effects on benthic macrofauna

Guidelines issued by the Department of Conservation to assist the assessment of marine farm proposals highlight the need to avoid smothering of reef habitats by biodeposits (DoC 1995). For this reason, mussel farms in New Zealand have usually been located over areas of soft-sediments. Only limited research has been done, however, on the effects of mussel culture on the soft-sediment fauna of New Zealand inlets (Kaspar *et al.* 1985). Assessments of the environmental effects of farm proposals based on the DoC guidelines usually contain only qualitative descriptions of large, conspicuous species that inhabit the surface of the sediments. There has been a distinct lack of data on sediment-dwelling infauna and a lack of on-going monitoring to determine the long-term effects of mussel farms.

Overseas studies, predominantly of the culture of *Mytilus* species, have also been compromised because they usually do not adequately distinguish between the large spatial and temporal variability in the natural assemblages of soft-sediment habitats and the effects caused by mussel culture. Nevertheless, some consistent trends have emerged. Organic enrichment of the sediments beneath mussel farms is frequently accompanied by a decline in the abundance of large, deep-burrowing species of molluscs (particularly suspension-feeding bivalves), echinoderms, crustaceans and polychaetes (marine worms), and an increase in the relative abundance of surface-feeding gastropods and small, opportunistic species of polychaetes, nemerteans and crustaceans (Tenore *et al.* 1982, Mattsson and Lindén 1983, Grant *et al.* 1995, Stenton-Dozey *et al.* 1999). Less consistent changes include a decline in species diversity and overall faunal abundance (Tenore *et al.* 1982, Mattsson and Lindén 1983). The loss of active, burrowing infauna that turn-over and oxygenate the sediments exacerbates the anoxic conditions caused by organic enrichment.

Other changes to the benthic fauna are associated with the accumulation of mussels, mussel shells, and other debris on the sediments beneath farms. As they grow, large mussels and their associated fouling fauna are occasionally displaced from the lines or are dislodged during storms or harvesting. Large densities may accumulate under older farm sites. Cole and Grange (1996) recorded densities of up to 400 mussels.m^{-2} beneath farms in Beatrix Bay and estimated that the biomass represented around 5% of the farmed mussels in the bay. Clumps of mussels beneath the farms become colonised by other organisms and provide reef-like habitat for a variety of small fishes and mobile fauna. They also tend to attract large numbers of predatory fish, starfish, crabs, sea urchins and other echinoderms (Tenore *et al.* 1982, Mattsson and Lindén 1983, Cole and Grange 1996). Exclusion of trawling by the farm infrastructure also means

that species which are otherwise uncommon in open areas of seabed, such as scallops (*Pecten novaezelandiae*) and horse mussels (*Atrina zelandica*), are occasionally abundant beneath the farms.

3.3.3 Cumulative and diffuse impacts

Existing research suggests that the environmental effects of mussel biodeposits and shell-drop are largely restricted to the immediate footprint of the farm (Grange and Cole 1997, Kaiser *et al.* 1998, Stenton-Dozey *et al.* 1999). The total area of influence is determined by the size of the culture area and the direction and velocity of currents which transport material away from the long-lines. There have been no direct studies of the cumulative and diffuse effects of mussel culture on sheltered waterways. Such effects may be associated with the gradual accumulation of large numbers of small farms or the development of very large blocks in areas of limited water flow. In this section, we discuss potential cumulative impacts of mussel culture. However, it is important to stress that, as yet, most of the ecological effects that we review here have not been documented directly and should therefore be regarded only as "possible", rather than "probable", consequences of increasing farm development.

3.3.3.1 Off-farm impacts on community structure

Changes in the composition of natural assemblages in habitats surrounding marine farms may be effected by the activities of predators or other pests that are attracted to farmed embayments. Mussel farms attract predatory birds, fish, starfish, and crabs and may even enhance recruitment of these organisms to levels that create problems for production (Pryor *et al.* 1999). For example, juveniles of the small labrid fish, *Notolabrus celidotus*, or "spotty" appear to recruit around the anchor chains and moorings of New Zealand mussel lines (Carbines 1993). Adults of this and other species, such as snapper, are significant predators of small mussels (Clarke 1993, Hayden 1995). There is currently no information on the relationship between farm size and predatory attraction, or the degree to which mussel predators supplement their diet on surrounding fauna.

Large populations of reproductively active adult mussels in production farms have a correspondingly large output of competent eggs and sperm. Because the dynamics of rocky reef assemblages are strongly influenced by the supply of planktonic larvae (Underwood and Fairweather 1989, Menge *et al.* 1999), increases in the abundance and retention of mussel larvae in sheltered embayments could potentially cause shifts in patterns of space occupation on nearby rocky shores that have flow-on effects for other community interactions (e.g. competition and predation). The increased abundance of mussel larvae in farmed waterways may, therefore, result in gradual change in the composition of biological assemblages on natural rocky reef surfaces.

An associated question is whether predation by large densities of cultured mussels on zooplankton communities and competition with zooplankton for food (Horsted *et al.* 1988) have flow-on effects for the population dynamics of benthic species elsewhere in farmed embayments. This is likely only in bays that have poor flushing with outside areas. Many benthic species have a larval planktonic phase. It is possible that changes in the composition and abundance of zooplankton associated with intensive mussel rearing could effect long-term changes in the abundance of a range of benthic fauna. Such effects are unlikely to be detectable at low levels of farm development, but may become increasingly important as the number of farms and total bivalve biomass increase.

3.3.3.2 Changes in ecosystem function

In embayments with low productivity, large densities of farmed mussels may cause changes in phytoplankton abundance and nutrient cycling that have implications for the growth and survival of other animals (Haamer 1996). Rodhouse and Roden (1987) predicted that when greater than 50% of the primary productivity of an embayment is diverted to mussel-rearing, significant modifications of the environment and decreased production yield may occur. However, there is little empirical basis for this figure, since natural rates of primary production are extremely variable in space and time. The extent of changes in primary production will depend on the size of the bay and the extent of flushing by oceanic or freshwaters. Many of the models of production carrying capacity discussed earlier (Section 3.2) do not directly account for the proportion of primary production required by other benthic or pelagic organisms. Mussels are very efficient at surviving periods of low food abundance, but this is not necessarily true of many other benthic species, which may suffer during periods of low primary productivity.

Organic enrichment of small areas of the seabed of well-flushed embayments is unlikely to have much detectable impact on broad-scale patterns of nutrient exchange and phytoplankton abundance. As the total area covered by mussel farms increases, however, the contribution that mineralisation of biodeposits makes to bay-wide nutrient recycling will increase. Changes in the pattern of nutrient cycling have been linked to outbreaks of toxic red tide organisms (Cembella *et al.* 1997) and may indirectly affect recruitment of other important marine species. For example, it appears that blooms of the red tide dinoflagellate, *Gymnodinium mikimotoi*, in Japan are stimulated by increased release of ammonium and other micronutrients from the sea floor. Such release occurs following strong stratification, and subsequent mixing of the water column (Kimura *et al.* 1999). Ammonium efflux from the sediments is often greater in areas affected by the biodeposits of mussel farms (Grant *et al.* 1995), but it is unclear how these relatively small-scale effects may affect patterns of nutrient recycling over larger spatial areas.

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An extreme example of the types of ecosystem-level effects that large densities of suspension-feeding bivalves can have on coastal embayments was provided by the catastrophic elimination of intertidal mussel and cockle beds in the Dutch Wadden Sea in 1990. Dankers and Zuidema (1995) estimated a total initial population of $> 26 \times 10^9$ mussels in this area, but poor recruitment over a number of years, dredging by mussel fishermen and high natural mortality severely depleted stocks over a large area of the Sea. This mortality was subsequently followed by:

(1)   Exceptional blooms of planktonic diatoms,

(2)   Rapid growth of other, non-exploited molluscs,

(3)   Switching behaviour of mussel predators to alternative prey,

(4)   Increased mortality and lowered condition in wading bird populations, and

(5)   Exceptionally high recruitment of other benthos (Beukema and Cadee 1996, Dankers and Zuidema 1995).

It is unclear whether similar effects would be manifested by large-scale farm development, but this example serves to illustrate the important role that large bivalve populations can have on the ecology of sheltered coastal ecosystems.

3.3.3.3 Epidemiological effects

The physical infrastructure of mussel farms and the large number of mussels in close proximity can also act as a reservoir for the incubation and spread of nuisance organisms (Beveridge *et al.* 1994, Fuentes *et al.* 1995, Cayer *et al.* 1999). Tenore *et al.* (1982) have estimated that the biomass of fouling species on mussel culture systems may be as high as 67% of the mussel biomass. In New Zealand, fouling organisms of mussel longlines include introduced species of ascidian (*Ciona intestinalis*), macroalga, (*Undaria pinnatifida*), and mussels (*Mytilus galloprovincialis*). In some areas, these species are causing significant problems for mussel production. The increased habitat provided for fouling organisms by mussel farms can mean that their abundance within sheltered embayments is substantially greater than might otherwise be the case. This may also enable them to become established in natural habitats nearby. The spread of problem organisms is likely to be exacerbated by farm management practices (e.g. relocation of equipment) and could increase as the density of farms increases and there are fewer, undeveloped embayments between significant culture areas.

3.4   Social carrying capacity

Development of the mussel industry and other cultured shellfisheries has provided significant economic and employment opportunities for a number of areas of regional

New Zealand, most notably the Marlborough Sounds, Tasman and Golden Bays and Coromandel Peninsula. Continued growth of the industry will provide further opportunities for employment and the development of secondary processing facilities. Nevertheless, farm development may also have some negative effects on other users of coastal waterways. Sheltered inlets are used for a wide range of other commercial, recreational, cultural and aesthetic purposes that are not always compatible with marine farming. For example, the physical infrastructure of farms has a direct impact on some wild fisheries by excluding trawling from the vicinity of the farm. The types of social impacts that may arise from farm development include displacement of other existing uses of the waterways, decreased satisfaction and enjoyment of other users, change in the type of association people have with the area (e.g. perceptions of "natural" versus "modified" landscapes), or diminution of future opportunities. Each of these types of impacts can have associated economic and social costs that must be balanced against the benefits to employment and economic activity that may accrue from farm development.

Shelby and Heberlein (1986) proposed three "rules" for determining the social carrying capacity of an area:

1. *There must be a known relationship between the level of the activity* (in this case farm development) *and social impacts,*

2. *There must be agreement among relevant groups about the different types of opportunities to be provided in the area,*

3. *There must be agreement among relevant groups about appropriate levels of impact.*

Opposition to marine farm proposals in recent environment court hearings has often been on the grounds of impacts on navigation and safety, public access, visual quality and natural character (Anon. 1995). In some areas, the large floats, longlines and other infrastructure of mussel farms can be an impediment to the movement of vessels and may alter the visual quality of an area. The significance of impacts on navigation and access are likely to be related to the physical geography of the waterway and the amount of use it receives from other maritime and recreational activities.

Assessing the "natural character" of a coastal area involves judgements about its ecological condition (e.g. degree of existing modification of the natural environment) and perceptual features of the environment (i.e. how people evaluate different settings). Thus, changes in natural character involve not only physical modifications to the environment, but also the more complex issue of how those changes alter the types of personal associations that people have with the area. Landscape evaluation studies

in New Zealand (Fairweather and Swaffield 1999) and overseas (Kaplan and Kaplan 1989) show that perceptions of the "naturalness" of a setting are influenced by a key set of visual components of the landscape (e.g. relief, water, vegetation and the absence of signs of human modification), by their arrangement in the landscape, and by the personal attachment people have with the setting.

From a legal standpoint, case law has established that human-made structures and modifications do not necessarily remove the natural character of a coastal environment (*Hooker vs Waitemata City Council 1979 NZTPA 38*) and that an area does not have to be pristine to be "natural" (*Harrison and others vs Tasman District Council 1&2 NZPTD 702*). Nevertheless, there is recognition at both a policy level and in recent legal decisions that the impacts of farm development on visual amenity do not increase steadily as the size and number of farms increases. Rather, at a local scale, natural character is sensitive to new activities, not previously represented in the area, that may set a precedent for further development (*Pigeon Bay Aquaculture Ltd vs Canterbury Regional Council (C32/99)*). This is recognised in Policy 1.1.1 of the Coastal Policy Statement which establishes that natural character should be preserved by, among other things:

(a) encouraging appropriate subdivision, use or development in areas where the natural character has already been compromised and avoiding sprawling or sporadic subdivision, use or development in the coastal environment.

A corollary is that the social impacts of farm development are likely to be greater in undeveloped coastal areas than in areas that have already been modified by aquaculture or other coastal uses. Because the values people attach to particular environments are key elements of the definition of natural character (MfE 1998), the severity of any impacts will be dependent on the range and strength of associations that people have with an area. For this reason, proposals for development in largely unmodified embayments close to major centres of population or near culturally important sites are likely to be particularly contentious.

4   NIWA'S APPROACH TO ESTIMATING THE CARRYING CAPACITY OF NEW ZEALAND INLETS

NIWA's approach to estimating the carrying capacity of inlets for shellfish culture has been to define and numerically model the dynamic processes that affect the supply of food within an inlet and the utilisation of that food for shellfish growth and condition. It extends earlier ecosystem models by including a component that describes some feedback processes between bivalve populations and their food supply (Ross and James 1998). This is considered important because, as the intensity of bivalve culture increases, the shellfish themselves may have broad-scale effects on ecosystem processes by, for example,

affecting the rates of nutrient recycling within the system or changing the relative influence of zooplankton grazing. The NIWA programme addresses sustainable shellfish production in a range of geographic locations and incorporates several species of shellfish. The following discussion reviews the major facets of the mussel component of the programme.

Three separate models make up the overall model of mussel production carrying capacity:

- a hydrodynamics model that describes the physical transport processes in embayments. It simulates the effects of tides, freshwater inputs and weather on current flows, flushing rates and water column structure.

- an ecosystem model that simulates the processes which determine the distribution and abundance of phytoplankton, including the degree of water stratification, light penetration and intensity; nutrient supply and recycling within both the water column and sediments; and mortality, sedimentation and predation of the plankton. The end-product is a simulation of phytoplankton abundance.

- a mussel energetics model which describes what the mussel does with planktonic food. This includes its filtration rate, how much food is actually ingested and assimilated and the proportions allocated to growth and reproduction. The end-result is a simulation of growth and condition of mussels.

The first two components of the model determine the availability of food for the mussels. The third determines the relationship between the size structure of the population and how the mussels process the available food for growth and reproduction.

4.1   Model components

4.1.1   Hydrodynamics

The distribution, rate of production and supply of phytoplankton to culture areas depends upon the hydrography of the waterway. In estuaries, movement of suspended particles (including phytoplankton) is dominated by river flows, whereas in coastal inlets it may be determined more by tidal currents. As a general rule, inlets that have a small volume that is frequently flushed by water from outside the inlet (i.e. rapid turnover time) support denser populations of bivalves than those with limited water exchange and slow turnover times (Dame and Prins 1998). The latter have a greater potential for localised depletion of phytoplankton by large densities of bivalves.

During the initial stages of the NIWA programme, the primary focus has been on determining the mussel production capacity in Beatrix Bay, an embayment in Pelorus Sound where there are already about 37 mussels farms. Hydrodynamic studies showed that water in Beatrix Bay is stratified (i.e. in layers) for much of the year and that there are distinct differences in the speed and direction of currents in each layer that affect transport of phytoplankton. Stratification usually occurs when water of low salinity and/or high temperature overlies more saline, cooler waters. Movement and mixing of water in Beatrix Bay is strongly influenced by tidal currents and pulsed freshwater flow from the Pelorus River (Proctor and Hadfield 1998). Water circulation in Beatrix Bay has been simulated with and without the influence of wind and temperature. These simulations are being validated with data collected from current meters and drogues and are then used to estimate the transfer of water between the spatial "boxes" of the carrying capacity model. Initial results suggest that tidal flushing of the water in the bay occurs in 16 tidal cycles, or just over 8 days.

4.1.2   Primary Production

The vertical stability of the water, driven by freshwater inflow and thermal heating, is a major factor controlling the supply of light and nutrients to phytoplankton in the Marlborough Sounds. NIWA has linked year to year variability in phytoplankton abundance in Pelorus Sound to variability in the stratification of the water and freshwater inflows, primarily from the Pelorus River. In Beatrix Bay, phytoplankton growth is limited by nitrogen availability (Gibbs *et al.* 1992, Gibbs and Vant 1997). Highest concentrations of nitrogen occur over the winter months but, at this time, primary production is limited by low light availability. Localised depletion of phytoplankton in farms with large stock densities sometimes occurs in winter, when phytoplankton biomass is low. In summer, however, phytoplankton levels within the farms can be enhanced by ammonium production from the mussels (Ogilvie *et al.* 2000).

NIWA studies have identified four types of phytoplankton dynamic behaviour in New Zealand coastal inlets with different physical properties:

I.   *Seasonally stratified systems*. In these systems, spring phytoplankton levels increase markedly from low winter levels as water column stratification develops. The spring bloom is terminated in summer, either by nutrient depletion or by zooplankton grazing, and is followed by a period of low nutrients and high zooplankton biomass. Declining levels of zooplankton give rise to a further bloom in autumn, maintained by increasing nutrient concentrations, which are generally high throughout the winter period. As stratification breaks down, the depth at which mixing occurs increases and solar irradiance declines. Phytoplankton abundance declines to low winter levels.

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II. *Continuously stratified systems*. These systems are similar to Type I above but the greater stability of the water column in winter, results in lower vertical mixing of the phytoplankton. Hence phytoplankton are retained in upper water levels where there is more light, giving rise to greater primary production in winter. Nutrient levels also generally remain high in winter in this type of system.

III. *Weakly stratified systems*. In these systems, light controls phytoplankton growth over the whole year, with high levels of inorganic nutrients present throughout the water column. The mixing depth of the phytoplankton is large enough to prevent the development of a pronounced spring bloom.

IV. *Highly turbid systems*. Although they may be physically quite different, the phytoplankton and nutrient dynamics of these systems, are similar to weakly stratified systems because of low light penetration. Shallow estuarine systems may exhibit this behaviour due to high turbidity.

A shift from one type of behaviour to another can occur due to changes in the external inputs (e.g. freshwater, wind, temperature) which drive stratification of the water column. The consequences of such a change in behaviour can be significant. For example, during the winter of 1995, Pelorus Sound was well stratified and phytoplankton levels were high (Type II system). In 1996, stratification broke down during winter, (Type I system) caused by abnormally low freshwater inputs into the Sound, which resulted in lower phytoplankton levels (~30% of that recorded during winter 1995). The reduction in phytoplankton appears to have caused a significant decline in mussel condition throughout the Sound. Mussel growth was similarly affected. Lower levels of nitrate were present throughout spring-summer 1996/97, suggesting a loss of nutrient over the winter period associated with the low phytoplankton abundance. The reduced phytoplankton production during a breakdown in stratification appears to result in lower levels of nutrients being taken up and bound in the phytoplankton, and consequently lower levels of nutrient sedimentation. Over the winter period the bioavailable nutrient in Pelorus Sound equilibrates by exchange with external water from Cook Strait, so that there may have been a net loss of nutrients from the system, with lower levels of nutrients retained in sediments of the sounds. A year after the initial decline in mussel condition (winter 1996), bioavailable nutrient concentrations, phytoplankton abundance, and the condition had still not returned to previous levels. The lower than expected production resulted in short-term closures of processing factories due to farm stocks being in poor condition.

4.1.3   Mussel energetics

NIWA's mussel energetics model relates the abundance of mussel food, including phytoplankton and other particulate matter, to the growth and condition of the

mussels. Experiments have shown a range of functional relationships between food quality and quantity and the rates of filtration, ingestion and assimilation by *P. canaliculus*. A fully-grown mussel is capable of filtering up to 350 litres of water per day. The success of *P. canaliculus* in long-line culture is partly due to its ability to adjust its feeding rates over a wide range of plankton concentration and quality (Hawkins *et al.* 1999). The ability to adjust rates of particle absorption, independent of changes in the concentration of inorganic particulate matter suggest a potential for expansion of farming away from traditional 'clear water' sites to more turbid areas (Hawkins *et al.* 1999).

One of the important findings of these studies was that below about 0.5 μg/litre of chlorophyll (an indicator of phytoplankton abundance), growth of the mussels drops off quickly and they begin to lose condition. This information has been used to develop some generic guidelines for the sustainability of farms in different regions (Box 1).

NIWA's ecosystem models were developed originally to answer questions about the potential for food depletion by mussel culture in Beatrix Bay. They were able to establish that reduced mussel growth within the New Zealand Greenshell ™ industry from 1996 to 1998 was most likely due to food limitation associated with natural variations in nutrient and phytoplankton availability and was not a direct consequence of stocking density. Field sampling has shown the potential for some short-term, localised depletion of phytoplankton levels within the boundaries of mussel farms (Olgilvie *et al.* 2000), but as yet, any broader-scale, ecosystem effects have not been documented.

Although NIWA is still working on model validation, we have been able to make preliminary estimates of production carrying capacity in Beatrix Bay. An example of two different outputs which have been obtained from the model are the time it would take for mussels to grow to 100 mm at a range of stocking levels in the bay and secondly, the harvestable yield (tonnes) which would be available at different stocking levels. At present, about 2500 tonnes of mussels are produced annually in each of the two sides of Beatrix Bay. At this stocking density, mussels on the western side of the bay take just over 14 months to reach 100 mm while those on the eastern side take almost 16 months, a difference of 7 weeks. On the western side of Beatrix Bay, the time taken to reach 100 mm increases almost linearly with increasing stocking level but on the eastern side of the bay, the minimum time to reach 100 mm remains constant up to a stock level of ~6000 tonnes and then starts to increase as stocking levels are further increased. Potential meat yield increases on both sides of the bay up to a stock level of about 6 000 tonnes. Beyond this, meat yield continues to increase in the eastern side of the bay, but starts to level out in the west.

Box 1. Generic guidelines for levels of phytoplankton abundance and water velocity for sustainable mussel culture.

Food levels

- *Chlorophyll <0.5 µg/l* – very poor growing conditions, very slow growth and loss of condition if for a prolonged period

- *Chlorophyll in range 0.5-1 µg/l* – generally poor growing conditions. Mussels grow slowly and may not lose condition, but recovery following spawning is slow, and it takes a long time to reach harvestable size.

- *Chlorophyll in range 1-2 µg/l.* Moderate growing conditions, mussels of reasonable condition if interspersed with periods of higher chlorophyll concentration.

- *Chlorophyll in range 2-4 µg/l.* Good growing, likely to achieve harvestable size in 10-12 months. Mussels should achieve good condition with rapid recovery from spawning.

- *Chlorophyll in range 4-8 µg/l.* Ideal growing conditions. Likely to be rare, fast growth.

- *Chlorophyll > 8 µg/l.* Little known, could be good growing but food handling difficulties.

Water currents

- *Velocity <5 cm/s.* - very weak current, poor mass flux and inconsistent current direction. Depletion likely at the centre of farms. Only suitable for low density farming or spat holding.

- *Velocity 5-10cm/s.* - weak current velocities of generally widely varying direction leading to some depletion at centre of farm.

- *Velocity 10-20cm/s.* - moderate-low depletion that may be more marked at downstream end of farm. Depletion is more likely to be observed in centre of farmed area.

- *Velocity >20cm/s.* - strong current flow. Little depletion but cumulative effect of many ropes/longlines in the direction of flow could result in

4.2   Extending the existing carrying capacity model

4.2.1   Transferability

NIWA's models are transferable to new locations and situations, but their utility in simulating the effects of new farm development depends on the ability to calibrate and validate the models with a set of physical and biological data from the new location. We have outlined some of these data requirements in Table 3. For the models to be run in a new coastal area, data are required on the local bathymetry, meteorology, currents, and fluxes of phytoplankton and nutrients into and out of the study area (indicated by "†" in Table 3). Other sources of data, such as those on mussel growth

and movement of nutrients among different sinks within the system (indicated by "‡" in Table 3), are used to refine the model's performance to local conditions.

An important future challenge for NIWA's research will be to extend the application of the models to new geographic areas in New Zealand and to other types of environments where marine farm development is likely to occur (e.g. open water). This extension is best achieved in advance of, or contemporaneous with new farm development, so that changes associated with mussel culture can be compared against a baseline of natural variability in system behaviour. This requires a commitment to monitoring a range of the regional and site-specific environmental data outlined in Table 3 in order to calibrate the models for the new situation.

TABLE 3. *Description of the purpose and data requirements of each submodel within NIWA's carrying capacity models.*

Type of model	Purpose	Data requirements
1) Hydrodynamics model	To simulate patterns of water flushing among grid cells (spatial units) within the study area. To generate fluxes of food or nutrients within the bay.	†Bathymetric data – to develop 3D grid-cells. †Long-term (preferably > 3 yrs) meteorological and freshwater input data to drive the model. †Current velocities for model validation.
2) Mussel energetics model	To predict the growth, condition and mortality of mussels under different environmental conditions.	‡Data on growth, condition and reproductive state of cultured bivalves. ‡Data on mussel response to variation in food quality and quantity.
3) Ecosystem model	To predict the distribution, abundance and production of phytoplankton. The modelling platform. It uses outputs from the hydrodynamics model and the mussel energetics model to generate estimates of carrying capacity.	†Boundary data to generate fluxes of phytoplankton and nutrients (C, N) into and out of the study area/embayment to drive the model. ‡Data on surface light availability and underwater attenuation †Time series monitoring of phytoplankton and nutrients within the area modelled to calibrate the models. ‡Data on fluxes of nutrients and phytoplankton to and from other significant sinks (e.g. zooplankton, and natural populations of filter feeders).

4.2.2 Issues of scale and resolution

As discussed in Section 3.2, the spatial resolution of carrying capacity models is determined by management objectives and the resources available to collect data from

a larger number of grid points within the study area. NIWA's hydrodynamic model for Beatrix Bay is divided into spatial units that represent a spacing of 250m (Proctor and Hadfield 1998). However, in common with most ecosystem models, the spatial units ("boxes") currently used in NIWA's ecosystem model are relatively coarse (each box has dimensions in the order of several kilometres). This means that it has limited utility in resolving smaller-scale issues related to the area and location of individual farms within an embayment, as the model assumes a relatively even spread of mussels within each box. NIWA is currently working to improve the spatial resolution of the models to address some of these issues.

A related issue of scale is highlighted by recent changes in the areal coverage of proposed individual farms (MacKay 2000). The concentration of filter-feeding and biodeposits in particular areas of an embayment by large farms or aggregations of many small farms may cause significant shifts in the pattern of nutrient availability and overall system behaviour that are too subtle to be predicted from existing models (Section 3.3.2). Refinement of the models to address these issues necessitates a change in focus and in the scale at which field and experimental data are collected to calibrate the models (Thrush *et al.* 1997).

As an example, we have provided a preliminary summary of the possible direct and indirect environmental effects of mussel culture that are possible at very intensive levels of farm development, and the spatial scales at which they are likely to be important (Table 4). Again, it is important to stress that, at current levels of marine farm development in New Zealand, only some of the direct effects such as shell-drop, attraction of predators and impacts on visual amenity have been documented, and that the severity depends upon the situation and management of the farm. Nevertheless, increasing intensification of bivalve culture within a region may be associated with subtle, broad-scale environmental effects that are not predictable from site-specific assessments. Such broad-scale effects must be investigated on a similarly broad spatial scale and are likely to affect a greater range of stakeholders.

5   IMPLICATIONS FOR FUTURE MONITORING AND ASSESSMENT

Under the Resource Management Act (RMA), marine farms are required to have no significant "adverse effects" on their surrounding environment (Grange and Cole 1997). The term "effect" is broadly defined in the Act and requires consideration of direct, indirect and cumulative impacts across a broad range of spatial scales of inquiry (Box 2). Past environmental assessments of marine farms have typically been reactive surveys of the direct impacts of individual holdings and have neglected

TABLE 4. Summary of realised and potential issues associated with increasing intensification of bivalve culture at a hierarchy of spatial scales of investigation

Spatial scale of effect	Issue	Stakeholders affected if effect is significant
Rope ("dropper")	Phytoplankton depletion	Marine farmer
Farm	Phytoplankton depletion	Marine farmer and neighbours
	Organic enrichment and impacts on infauna	Conservation agencies (where the farm location may affect significant natural habitats)
	Shell-debris	
	Shading of benthic habitats	
	Attraction of mobile predators	Coastal residents
	Impacts on visual amenity and natural character	Local iwi
		Recreational fishers
	Exclusion of wild fisheries	Commercial fishers
Embayment	Phytoplankton depletion	All marine farms in the embayment
	Organic enrichment and impacts on infauna	Conservation agencies (where the farm location may affect significant natural habitats)
	Shell-debris	
	Shading of benthic habitats	
	Attraction of mobile predators	
	Epidemiological effects	Coastal residents
	Competition with zooplankton and other plankton feeders	Local iwi
		Recreational and commercial boat traffic
	Off-farm impacts on natural communities	Other stakeholders (e.g. tourism operators)
	Impacts on visual amenity and natural character	On-shore production facilities
	Exclusion of wild fisheries	Recreational fishers
	Displacement of existing use	Commercial fishers
	Impacts on Tikanga Maori and mahinga maataitai	
Multiple embayments (region)	Phytoplankton depletion	All marine farms in the region
	Organic enrichment and impacts on infauna	Conservation agencies
		Coastal residents
	Shell-debris	Local iwi
	Shading of benthic habitats	Recreational fishers
	Attraction of mobile predators	Commercial fishers
	Epidemiological effects	Recreational and commercial boat traffic
	Competition with zooplankton and other plankton feeders	
	Off-farm impacts on natural communities	Other stakeholders (e.g. tourism operators and their clients)
	Subtle, long-term effects on factors affecting primary production	Coastal business owners
	Impacts on visual amenity and natural character	
	Exclusion of wild fisheries	
	Displacement of existing use	
	Impacts on Tikanga Maori and mahinga maataitai	

diffuse and cumulative effects that may accrue from expansion of the industry (Section 3.3). Detailed monitoring of farm sites has rarely been undertaken once the farm is established and has been restricted to measurements of environmental variables that directly affect mussel production, such as water quality and phytoplankton abundance. As a result, there is little information on long-term changes in the ecology of farmed embayments and their general surroundings that may have accompanied growth of the industry.

Cumulative impacts can only be assessed against a baseline of changes that are known to have already occurred in the environment as a result of existing and past activities (McCold and Salisbury 1996). Any cumulative effects of marine farming are likely to be subtle, broad-scale and to have developed over a number of years (see Section 3.3.3). They are unlikely to be detected by conventional, site-specific approaches to environmental assessment, but require a commitment to strategic, regional-scale assessment and modelling.

Box 2. Definition of environmental "effect" under the RMA (MfE 1999)

The term "effect" includes:

(a) positive or adverse effects;

(b) temporary or permanent effects;

(c) past, present, or future effects; and

(d) cumulative effects, which arise over time or in combination with other effects – regardless of the scale, intensity, duration, or frequency of the effect.

"Cumulative effects" have been established as:

- An adverse cumulative effect is one that, in combination with other effects, is significant only when it breaches a threshold. Consideration of cumulative effects should focus on the scale and nature of effects in combination.

- The concept of cumulative effects presupposes that environmental thresholds (upper and lower limits) are set. These may vary according to the resource and the community's values

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Direct evidence of past cumulative effects is not possible, but a case may be built by using several lines of inquiry concurrently (Wiens and Parker 1995). These could include:

- Development, testing and monitoring of indicators of regional ecosystem condition

- Use of archival information to reconstruct historical baselines for natural assemblages,

- Sampling and experiments along a gradient of intensity of marine farm development to determine differences among embayments subject to different levels of marine farming,

- Comparison with reference areas that remain unaffected by marine farms,

- Analytical surveys and focus-groups of other users of farmed embayments to develop methods for predicting and assessing social and cultural effects of marine farm development.

- Adaptive monitoring of new farm developments (and appropriate reference areas) to characterise the environmental effects of novel types of farms (e.g. particularly large holdings), in new locations (e.g. open coast).

It is important that any future research – including monitoring studies – is structured in such a way that it contributes to a greater ability to predict the impacts of new farm developments and is not simply aimed at describing existing conditions. One way in which this could be achieved is to ensure that the research can be integrated with existing carrying capacity models to provide a broader understanding of the interactions of marine farms with other ecosystem components. Simulation models are important tools for adaptive management because they provide a conceptual platform for organising data collection and are able to simulate the consequences of specific management actions (Walters and Holling 1990).

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