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Manatū Ahu Matua

LITERATURE REVIEW OF ECOLOGICAL EFFECTS OF AQUACULTURE

Pelagic Effects

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2.1 Introduction

This chapter deals with near-field (approximately at the scale of the farm) pelagic effects (those seen in the water column). This should be read in conjunction with the benthic effects chapter (Chapter 3), where many of the wastes expelled into the pelagic zone will settle, and the cumulative effects chapter (Chapter 11), which deals with pelagic effects at larger scales.

All current sea-based aquaculture in New Zealand is suspended culture, either mussels on ropes, oysters on intertidal racks or finfish in cages. The pelagic zone is thus both the zone from which food is extracted by filter feeders and the first receiving environment for fish pellets and the excretory products of cultured animals and other waste material from attached fouling organisms.

Cultured finfish require feed-in diets high in protein and fat (Reid 2007), which means that the waste products (faeces, uneaten feed and ammonia) entering the pelagic system will contain additive components over and above natural levels.

Mussels and oysters, grown in suspended culture, extract phytoplankton, microzooplankton and organic particulates from the water column. Metabolic waste is released as faeces and pseudofaeces (rejected food in a loosely bound mucus strand). Shellfish faeces differ from that of finfish in being bound in long strands composed of digested and undigested plankton whereas finfish faeces emerge as a particulate “cloud” that disperses rapidly and is comprised of metabolised protein and fats. The difference between shellfish and finfish faeces can result in different biochemical impacts on the pelagic zone. Shellfish filtration can also have potential impacts on natural populations of plankton (reduction in abundance and changes in species composition). Therefore the potential pelagic impacts from finfish and shellfish aquaculture are treated in separate sections below.

Organisms that function at trophic levels lower than finfish and shellfish and that have imminent potential for culture in New Zealand, such as seaweeds (macroalgae) and deposit feeding sea cucumbers, have less significant ecological effects on the pelagic environment since seaweeds utilise dissolved nutrients (mainly Dissolved Inorganic Nitrogen (DIN)) for growth and sea cucumbers feed on organic material on the surface of the seabed.

Dissolved farm waste has the potential to increase ambient DIN to levels that can stimulate excessive phytoplankton production. Solid waste can settle out to the seabed or remain suspended as fine particulates that can increase turbidity and hence reduce light penetration within the farmed area. Organic particles can be remineralised thus contributing further to the dissolved inorganic fraction. Most of these impacts are at the farm-scale, but if the farm is placed in deep water (more than 25 metres) with high currents, impacts on the pelagic system will be reduced.

The significance of these key impacts depends on the assimilation capacity (or carrying capacity) of the environment. In shallow areas with slow currents, effects will be more pronounced in the near field compared with a deep site with strong flow and good flushing. In New Zealand, most mussel and oyster farms are located in areas that are well flushed since product yield is dependent on a sustainable delivery of plankton.

There is a large volume of international literature on the effects of shellfish and salmon farming on the pelagic environment and much of this material is referenced in three local reviews: finfish (Forrest et al. 2007b), shellfish (Keeley et al. 2009) and oysters (Forrest et al. 2007a). Further information for this section is drawn from published literature not covered in the reviews and client reports prepared for the Ministry for Primary Industries and regional councils. Some information is constrained by intellectual property (IP) agreements and so, for this information, only broad perspectives of impact are presented.

2.2 Feed added (salmon, kingfish and hapuku)

2.2.1 Main factors affecting the extent of pelagic effects

The magnitude and spatial extent of pelagic effects from finfish farms are a function of a number of inter-related factors, that can be broadly considered as farm attributes and physical environment attributes.

2.2.1.1 Farm attributes

Farm attributes (husbandry, management and farm design) that can affect the amount of dissolved nutrients and solid waste entering the water column include the following.

- Farm density: Density of farms in a unit volume of water.
- Stocking density: Salmon have a seasonal production cycle dictated mainly by ambient temperature, which means the amount of feed per fish varies during the year. Stocking density varies and this in turn will also influence the magnitude of waste loading to the water column.
- Feed conversion ratio (FCR): FCR is a measure of the efficiency of growth relative to feed used, specifically the weight of feed used divided by the amount of weight gained. The most efficient ratio is 1, all feed is converted to fish biomass, but in reality the global range is 1.1 to 1.7 on average (Reid 2007). The use of FCRs in assessing the impact of faeces and DIN on the environment is complex and the reader is referred to Section 5.1 of Reid (2007) for a full discussion.
- Cage design and orientation: Cage design and orientation to prevailing current direction impact the drag on passing water masses, flushing of cages and settlement of biofouling organisms.

2.2.1.2 Physical site attributes

The physical attributes of a finfish culture site that most influence its pelagic impact are temperature, the depth of water and current speed. The latter two dictate the magnitude and spatial extent to which dissolved and solid farm waste are dispersed through near-field water column. Secondary benefits from a well-placed site are increased oxygen delivery to the water column and benthos and maintenance of healthy benthic–pelagic coupling.

2.2.1.3 Overview of pelagic effects

The significant effects of finfish waste on the integrity and functioning of the near-field pelagic system are addressed in this section. The potential pelagic effects from finfish farming (not covered under specialist sections elsewhere for example biosecurity (chapter 7), escapee effects (Chapter 8) and effects on wild fish (chapter 5) can be categorised as:

- dissolved nutrients;
- solid waste;
- depletion of dissolved oxygen (DO).

2.2.2 Descriptions of main effects and their significance

2.2.2.1 Dissolved nutrients

Summary

Dissolved inorganic nutrients are released into the pelagic environment from finfish cages either directly, as fish excretory products (e.g. ammonium and urea), or indirectly as a result of remineralisation of particulate organic waste (Navarro et al. 2008). Nitrogen is often a limiting nutrient for phytoplankton production, and the introduction of inorganic nutrients has the potential to enhance the growth of phytoplankton (Wu et al. 1994) and at high concentrations can cause harmful algal blooms (Sorokin et al. 1996). Internationally, there have been experiences of blooms of species that produce biotoxins, some of which can be directly toxic to fish, and others which can accumulate in shellfish and affect consumers. As far as is known to date, salmon farming in New Zealand has not given rise to any harmful agal blooms and such effects are unlikely in the near future unless considerable new development occurs (Forrest et al. 2007b).

Symptoms of eutrophication or nutrient enrichment include the formation of algal blooms that can potentially reduce water clarity (and consequently sunlight availability to other phytoplankton in the water column) and strip oxygen from the water column once the blooms decay (Wetzel 1983). Since nitrogen and phosphorus are waste products from finfish farming, there is the potential to promote eutrophic conditions either by supplying a readily available nutrient source directly to phytoplankton or through oxygen removal via the bacterial decomposition of waste solids.

Nutrient enrichment may also lead to changes in phytoplankton species composition via altered nutrient ratios with, for example, an increased N:Si ratio favouring the growth of flagellates rather than diatoms (Officer & Ryther 1980). Dissolved organic nutrients are released from fish farms indirectly via dissolution of particulate organic waste and are likely, due to the high nutritional content of waste food and faeces, to represent a highly labile source of nutrients for heterotrophic bacteria.

Table 2.1: Pelagic effects associated with dissolved nutrients from feed-added aquaculture operations.

Description of effect(s)	Dissolved nutrients (mainly ammonia) are released as finfish excretory products. Nutrient enrichment of the water column above natural levels (i.e. eutrophication) can potentially lead to enhanced phytoplankton growth, including harmful algal blooms (HABs) and changes in phytoplankton species composition. Bloom decay (and increased microbial activity) can lead to reduced DO levels.
Spatial scale	*Localised*. Effects are most evident inside a farm and in the primary pelagic footprint with a strong gradient of decreasing impact with increasing distance. The intensity and spatial extent of enrichment is highly site specific, with high flow, deep sites producing larger but more “diluted” footprints.
Duration	Variable between grow-out periods when fish stocking densities change.
Management options	Can be partially controlled through: • careful site selection; • maintaining appropriate stock densities/feeding rates and matching farm placement and design to the site; • monitoring and ongoing adaptive management. Impacts are reversible upon removal of farm.
Knowledge gaps	Baseline dissolved nutrient concentrations in areas suitable for finfish farm development. New studies are required to determine changes in water column variables in areas of intensive finfish aquaculture. Enrichment effects on bacterioplankton. Hydrodynamic and biophysical model development to predict impacts and field data to validate models.

* Italicised text in this table is defined in chapter 1 – Introduction.

According to Navarro et al. (2008), few studies have examined the effect of finfish farm inputs on the phytoplankton community composition or production but several have indirectly examined the effect of inputs on the autotrophic microbial community by using chlorophyll concentration as a proxy for phytoplankton biomass. The majority of these studies concluded that chlorophyll concentrations are not enhanced by nutrient inputs from fish farms.

Rapid water exchange in coastal waters may also disperse phytoplankton, and in this respect it is significant that macrophyte growth has been shown to be stimulated by fish farm effluents (Neori et al. 2004). Hydrographic conditions are clearly important in dictating the degree of impact of fish farm inputs on pelagic ecosystems.

The response of the heterotrophic planktonic microbial community to fish farm inputs has received even less attention than that of the autotrophic community (Navarro et al. 2008). Of the few, mostly seasonal studies published, some have recorded enhanced bacterioplankton abundance near fish farms (La Rosa et al. 2002; Sakami et al. 2003; Pitta et al. 2006; Navarro et al. 2008) while others have not (Alongi et al. 2003; Maldonado et al. 2005). Navarro et al. (2008) suggest that the heterotrophic bacteria play a significant part is processing organic particulates released from farms.

Monitoring results for New Zealand salmon farms in the Marlborough Sounds and Big Glory Bay suggest that nutrient concentrations sufficient to cause significant enrichment as a result of farm inputs have not been reached (Hopkins 2004; Forrest et al. 2007b). Phytoplankton blooms have been recorded and harmful species detected throughout the Sounds; however, these appear to be regional phenomena and driven by processes that are unrelated to salmon farming activities. For example, a HAB that led to the relocation of a salmon farm in the Marlborough Sounds was determined to have been caused by larger-scale oceanic processes (Forrest et al. 2007b).

In the past few years, computing resources and numerical modelling systems have advanced considerably. This has enabled the evolution of models and integrated model suites that can mimic physical forcing and biogeochemical processes in marine systems and model the systems response to stressors. The main goals of applying a modelling approach to aquaculture include acquiring information on potential environmental impacts, designing of monitoring strategies and understanding the processes of a particular system (Silvert & Cromey 2001). Models should be used early on in the process of aquaculture development since they can not only identify potential problem areas with regard to environmental effects, but also can help in determining carrying capacities and setting sustainable feed levels for finfish.

A selection of models applicable to a range of environments and conditions is available (Magill et al. 2006; Stigebrandt et al. 2004; Tett et al. 2003). Existing models can provide crucial information and decision support when needed, however, they are limited by lack of ecosystem integration, a limited number of species interactions and their scale. Considering that fish farming impact is introduced into the system through the lower trophic levels where phytoplankton and bacteria are key players, it is important that any model used must incorporate a detailed description of the system in terms of both organisms and processes.

Planned expansion of finfish culture in New Zealand has prompted the use of models to predict the potential impact of proposed finfish farms on the water column in a number of bays (Zeldis 2008; Zeldis et al. 2010, 2011a). The most important finding from these client reports was that local hydrodynamics, water depth and ambient oxygen levels were the most critical factors for determining the sustainability of planned expansion of finfish farming.

2.2.2.2 Solid waste

Summary

Solid waste is made up of uneaten feed pellets and faecal material. The physical properties and chemical composition of the solid waste will in part dictate the potential for environmental effect (Reid 2007). It has been well documented in the literature that solid waste settling out of the water column onto the seabed can have significant impacts on the biogeophysical properties of benthic habitats (see Chapter 3). Pelagic effects are less well understood or quantified.

Faecal and feed material that remains suspended (or is resuspended from the seafloor into the water column) is fragmented by turbulence and the grazing activity of pelagic organisms such zooplankton and bacterioplankton (Olsen 2007). As with the fibrous indigestible portion of feed, faeces also have traces of micronutrients, such as dietary copper

Table 2.2: Pelagic effects associated with solid waste from feed-added aquaculture operations.

Description of effect(s)	Solid waste is released as faeces and uneaten feed, which have the potential to increase localised turbidity, which in turn can reduce light penetration through the water column thereby inhibiting photosynthetic (i.e. phytoplankton, benthic micro-algal and macro-algal) production. Organic particle enrichment has the potential to enhance rates of bacterial heterotrophic activity which can reduce oxygen levels.
Spatial scale	*Localised.* Effects most evident inside and in close proximity to cages. Levels decrease with increasing distance away from cages. The intensity and spatial extent of enrichment is highly site specific, with high flow, deep sites producing larger but more diffuse footprints.
Duration	Variable depending on fish stocking densities and local hydrodynamics.
Management options	Can be partially controlled through: • careful site selection; • altering feed capacities (and farm production/intensity) and matching farm placement and design to site; • monitoring and ongoing adaptive management; • impacts reversible upon removal of farm; • reducing biofouling on nets by regular cleaning and removal of biofouling waste. Impacts reversible upon removal of farm.
Knowledge gaps	Baseline data on natural suspended particulates in areas where finfish farming development is proposed. Enrichment effects on bacterioplankton. Models to predict dispersion and resuspension of fine particulates.

* Italicised text in this table is defined in chapter 1 – Introduction.

and zinc that, depending on feed concentrations and farming methodologies, is of environmental concern to pelagic food webs (Reid 2007). If a salmon farm is proximal to a mussel farm, as advocated in Integrated Multi-trophic Aquaculture (IMTA) (Chopin et al. 2008), a portion of small particles will be filtered out by the mussels. Filtering biofouling organisms on the cages, such as ascidians and blue mussels, will also remove some of the suspended faecal particulates. Most of this material, however, will settle on the seabed.

Through bacterial digestion, dissolved organic nitrogen and carbon (DON and DOC) are released from particulate waste into the water column. DOC is comprised of both labile (digestible) and non-labile components, the latter having relatively long turnover times in seawater (Olsen 2007). Labile DOC is readily and rapidly utilised further by bacterial heterotrophs while the fate of non-labile DOC is not well understood in the pelagic system.

2.2.2.3 Oxygen depletion

Summary

One component of water quality, DO, is particularly critical for the survival and good performance of farmed salmon. As a result, most farms regularly measure DO levels (in mg/l), which fluctuate naturally in the environment due to temperature shifts, time of day and upwelling of oxygen-poor waters from deep in the ocean. However, the primary mechanism for DO depletion is uptake by the fish themselves through respiration. This can result in significant depletion (below 50 to 60 percent oxygen saturation, Reid 2007) within and potentially down current from the cages. The problem is only likely to occur where flushing rates are insufficient (on scales of many days to weeks).

DO provides a useful overall proxy for a water body's ability to support healthy biodiversity and supplements the benthic indicators that will also pick up excessive nutrient loading. Salmon ideally need a level of dissolved oxygen over 5 mg/l to avoid oxygen stress, although they are able to live under lower oxygen concentrations, particularly if it is only for short periods of time (SCSAD 2010).

There are a number of processes that can deplete oxygen around a finfish farm. Since DIN is often a limiting nutrient for phytoplankton growth in the marine environment, an outside source of DIN above ambient levels can cause large algal blooms (MacKenzie et al. 2011). During subsequent decay of these blooms, oxygen can potentially be stripped from the water column. Microbial degradation of suspended organic particulate waste can also cause oxygen depletion as can the respiratory activities of the cultured finfish. However, episodes of oxygen depletion would be seasonal depending on fish stocking densities and water column temperature and stratification.

Table 2.3: Pelagic effects associated with oxygen depletion due to feed-added aquaculture operations.

Description of effect(s)	The primary cause of oxygen depletion inside salmon cages is through respiration of cultured fish. Decay of organic farm waste and/or phytoplankton blooms through heterotrophic bacterial activity can contribute to stripping oxygen from the water column. Oxygen depletion can cause the stress or death of culture fish and other pelagic organisms
Spatial scale	*Localised.*
Duration	Variable – Depending on stocking density, water temperature and flushing rates.
Probability	Unlikely to likely – Depending on seasonal fish stocking densities, temperature and water stratification.
Management options	Can be partially controlled through: • careful site selection; • altering feed capacities (and farm production/intensity) and matching farm placement and design to site; • monitoring and ongoing adaptive management. Impacts reversible upon removal of farm.
Knowledge gaps	Integration of hydrodynamic models with environmental oxygen saturation levels to predict the spatial and temporal scale of the impacts of finfish aquaculture.

* Italicised text in this table is defined in chapter 1 – Introduction.

Excessive oxygen depletion in the water column could potentially stress or kill the fish and other animals, with sediment DO depletion resulting in the release of toxic by-products (e.g. hydrogen sulphide) into the water, which can also have adverse effects on fish and other organisms. (Forrest et al. 2007b). Significant depletion of water column concentrations of DO at finfish farms overseas has usually only been observed when cages are heavily stocked or where they are located in shallow sites with weak flushing (La Rosa et al. 2002).

In New Zealand, monitoring data from existing salmon aquaculture operations reveal that water column DO concentrations do not become significantly depleted and are managed well at individual farms (Forrest et al. 2007b). Maintenance of adequate DO levels is critical to the survival of the farmed stock. In relation to future development in New Zealand, DO depletion is an issue that may need to be considered if, for example, multiple farms in close proximity are proposed. In such instances, there is the potential for DO to become increasingly depleted as water currents pass through sequential farms (Roper et al. 1998). It is generally considered that the greatest potential for adverse effects in the water column will occur in areas subject to poor flushing and a high stocking density (Wu et al. 1994; La Rosa et al. 2002).

2.2.3 Impact mitigation and management strategies

The major farming attributes dictating the magnitude of water column effects will be feed composition and application rate, feeding efficiency and finfish biomass per unit area while physical site attributes, such as water currents and flushing and water depth, are important mitigating factors (Forrest et al. 2007b). These factors can be influenced by appropriate initial site selection and subsequent farm management practices.

The New Zealand Finfish Aquaculture Environmental Code of Practice (2007) directs best industry practices throughout the hatchery, growing and harvesting cycle to minimise potential effects on the environment. A copy of these codes can be obtained from Aquaculture New Zealand (www.aquaculture.org.nz). To mitigate environmental impacts, the New Zealand government has a number of environmental controls in place, including the Resource Management Act 1991 (RMA) and the Fisheries Act 1996.

There are a number of important international publications that pertain to monitoring standards that have relevance to New Zealand finfish farming. The Food and Agriculture Organization (FAO 2009) of the United Nations reviews aquaculture environmental impact assessment and monitoring for a number of regions around the world (Africa, Asia-Pacific, Europe, North America and Latin America). There is also a section of this review that considers salmon aquaculture specifically and another that discusses the implementation of environmental impact assessments (EIAs) by country. Two Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) reports consider international aspects of reducing environmental impacts of coastal aquaculture (GESAMP 1991) and monitoring the ecological effects of coastal aquaculture (GESAMP 1996).

2.2.3.1 Mitigation

Site selection

Water column effects can be minimised by locating farms in deep areas (more than 25 metres) that have sufficient flushing to facilitate dispersal and environmental assimilation of farm wastes. These areas should also be characterised by well oxygenated waters over a seabed that has the capacity to assimilate waste without becoming anoxic and releasing hydrogen sulphide into the water column. Site selection should also recognise other possible loading of nitrogenous waste in the region to avoid a compounded DIN increase with the potential to stimulate phytoplankton blooms.

Feed control

From Forrest et al. (2007b):

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

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

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

Seasonal production cycles

Production cycles can be managed to avoid heavy stocking densities during periods of higher water temperature and lower ambient oxygen levels.

Integrated Multi-Trophic Aquaculture

IMTA is an emerging tool that is unproven in New Zealand but has shown considerable promise around salmon farms in Canada, (Chopin et al. 2001, 2004, 2008). In Canada IMTA systems typically combine finfish, mussels and sea weeds with caged deposit feeders (e.g. sea cucumbers, scallops, sea urchins) on the seabed or suspended under the finfish farm. This practice introduces the potential for both increased production per unit sea space as well as mitigation by the lower trophic levels of waste from feed-in cultures (Reid et al. 2008).

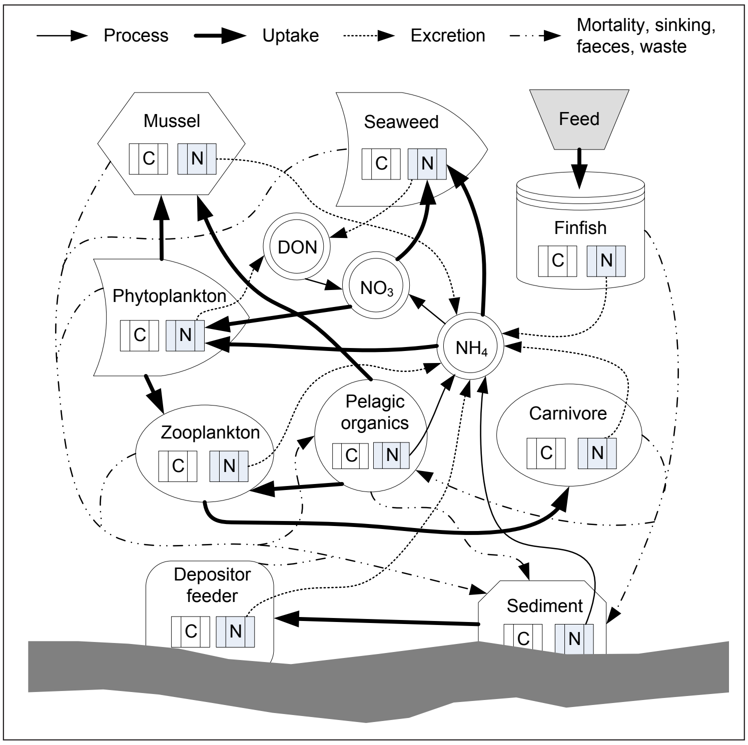
In the years since 2007, the concept has been adopted by the business world; IMTA systems are successfully operating in Canadian waters. Out of 96 sites in Southwestern New Brunswick, five sites have the combination salmon (or cod), mussels and kelps, and 11 other sites have been amended to develop IMTA as the industry progressively develops markets to absorb the co-cultured biomass.

To predict the mitigation role each co-culture species can serve in an IMTA operation, a preliminary model for an IMTA operation in New Zealand has been developed (Figure 1 from Ren et al. 2012) The model incorporates dynamic energy budgets of trophic species with an ecosystem model. It takes advantage of the similarity in the ecophysiological behaviour of species that describes the uptake and use of energy throughout an organism's life cycle. The model results have indicated that conversion of current monoculture into IMTA practices will reduce waste products and increase system productivity (Figure 2.1).

Model simulations show that a site supporting 1200 tonnes of salmon production (typical production from one site) can also support up to 22 tonnes of seaweed and 25 tonnes of sea cucumber production annually. The development of the model provides a research tool for assessment of IMTA practices to understand species interactions and predict productivity of IMTA farms. It should be added, however that no research has been conducted in New Zealand to date to validate this model.

IMTA technology may be particularly appropriate for New Zealand if conversions from mussels to finfish farms occur or if finfish farms are developed within the area of existing mussel culture. Models of cumulative effects should therefore accommodate the mitigation effects of shellfish production in the vicinity of fed aquaculture.

Figure 2.1: Conceptual diagram of the Integrated Multi-Trophic Aquaculture model in terms of carbon (C) and nitrogen (N) biomass



Source: Ren et al. (2012).

Notes: DON = dissolved organic nitrogen; NO_3 = nitrate; NH_4 = ammonia.

2.2.3.2 Monitoring and adaptive management

Monitoring and management plans that are adaptive to changing situations and scenarios could be a good way to guide the impact assessment of finfish farming on the pelagic environment. If these plans were part of regional integrated coastal zone planning then this could take into account all sources of nutrient loading into the pelagic environment.

Regional management

Once an area becomes a multi-development domain with numerous farms and possibly multiple species in one bay, plus other activities such as near-shore farming with associated effluent discharges, dredging, trawling, commercial shipping and sewage treatment, impact mitigation at the farm scale is not enough. Farm developments must then fit into regional coastal plans that take cognisance of all activities.

The projected growth of aquaculture in New Zealand underlines the need to integrate aquaculture management with regional coastal plans. It has been proposed in the international literature that the solution to managing cumulative effects is the development of an ecosystem approach to aquaculture (EAA) (Soto et al. 2008). The main ideas of EAA involve taking into account ecosystem functions and services, improvement of human wellbeing and equity and development in the context of other sectors, e.g. aquaculture nutrient input in the context of existing nutrient outputs from agriculture. Implications of these concerns and principles can be identified on farm, watershed and global scales.

The potential effect of multiple stressors on the marine environment is widely recognised. For example, the need for all stakeholders to be involved in protecting water quality in areas where shellfish aquaculture occurs is enshrined within the European Union (EU) water framework legislation. The EU Quality of Shellfish Growing Waters Directive (79/923/EEC) concerns the quality of the waters in areas designated by the Member States for growth of shellfish for human consumption. It defines guideline and imperative values for water quality. Member States must establish their own programmes for reducing or controlling pollution to shellfish waters to comply with these limits. Within these programmes, the requirement for maintaining water quality for aquaculture areas applies not only to marine farmers but to all stakeholders (regional councils, landowners and other water users) (SAFR 2008).

As discussed above, models provide a valuable tool for evaluating the potential impact of aquaculture and, therefore, are also a vital tool in regional planning. For example, biophysical models applied to existing and proposed mussel farming development in the Hauraki Gulf and Golden and Tasman Bays have assisted with maintaining the principles of EAA across a range of scales (Zeldis et al. 2010). The empirical data and model outputs have enabled Environment Waikato to set up a limits of acceptable change (LAC) adaptive management framework that seeks to manage impacts on a bay-wide scale for shellfish farming.

Site-specific monitoring

Existing salmon farms in New Zealand are located in embayments often in close proximity to mussel farms. Most monitoring to date has been on a site-by-site basis with an emphasis on benthic impacts. Big Glory Bay farmers support a monitoring programme that considers bay-wide water quality in terms of Chl-a, turbidity and oxygen levels but this is not adopted in other areas with salmon farming. While benthic monitoring at a site can indicate cumulative local effects, water column monitoring cannot identify a decisive site-specific impact. Dissolved nutrients and suspended waste particulates are rapidly diluted and dispersed once released from a farm. It is thus more appropriate to adopt a monitoring programme for a region with farm and control sites in alignment with prevailing hydrodynamic regimes. Assessing the water column for key parameters of nutrient enrichment will support good management practices to ensure that prolonged eutrophication is prevented.

Use of models

Coastal spatial planning requires the use of integrated modelling that can provide estimates of the scale of individual farm impacts but also place these in the context of multiple inputs within a bay or region and even in the context of other natural or anthropogenic inputs. Existing models consider both broader environmental effects and effects that directly impact on other aquaculture developments.

Impacts of single or multiple point source inputs of key indicator nutrients may be modelled to provide an estimate of the potential carrying capacity of an area prior to development. For example, Zeldis et al. (2010, 2011b) considered the impacts of aquaculture on nitrogen loading to the environment and also on the potential effects of natural reductions in oxygen saturation to predict the level of development of finfish farms in the Firth of Thames and Golden and Tasman Bays that could be sustained by the environment.

Models provide only an estimate of change and cannot fully account for the complexity of the real-world. When uncertainty exists around potential impacts, management strategies that allow staged development based on monitoring of appropriate environmental characteristics are required. The LAC framework (Zeldis 2008) sets trigger levels at local and regional scales to accommodate cumulative impacts from development in the context of a broader natural variability in these parameters. Stigebrandt et al. (2004) applied a similar concept for cumulative near-field impacts through a "model – ongrow – monitor" (MOM) approach to assess the impact of finfish development on a range of pelagic and benthic parameters.

Monitoring using models

Models must be calibrated against observations of real-world conditions. Baseline and operational monitoring programmes are required to provide spatial and temporal data to operate ecosystem models.

Baseline data is essential in designing an appropriate monitoring programme and provides reference data against which changes caused by farm waste can be measured. Appropriate monitoring sites may be identified through the use of hydrodynamic models that predict regions of greatest enrichment potential with consideration of cumulative effects from all sources.

To optimise resources, the level of monitoring (number of variables and frequency of monitoring) should be related to the size of the operation and the sensitivity of the receiving water body. Additional elements of monitoring programmes that need to be given careful consideration include: selection of reference stations; standardisation of sampling and analytical procedures; analysis and interpretation of data.

Given that a particular monitoring programme should be matched to the size, type and location of a coastal aquaculture development, it is not appropriate to recommend standard monitoring programmes.

2.2.4 Knowledge gaps

2.2.4.1 Baseline data

Assessment of changes in the pelagic environment can only be undertaken when there is reasonable background data to allow anthropogenic-derived change to be isolated from natural variation. For much of New Zealand's coastal water these data are either sporadic or absent, with few sites where long-term monitoring of key environmental parameters exists.

2.2.4.2 Model development

Hydrodynamic models

Model development is required in terms defining the effects of stratification on dispersal of particles. Most of New Zealand's coastal systems show some degree of thermal or saline stratification. Particles or nutrients trapped within stratified layers will move very differently from in a fully mixed water body. Resolving this issue is important in developing more accurate predictions of fish farm impacts at the regional scale.

Integration of hydrodynamic models and biochemical pelagic effects

Integration of hydrodynamic models with the variability in environmental parameters indicative of impact requires development. Such models could predict the spatial and temporal scale of oxygen depletion, nitrogen and bacterioplankton enrichment, phytoplankton production and particulate dispersion.

Model calibration

As with baseline data, there is a paucity of data available for calibration and validation of regional models. This is required to improve the accuracy of both hydrodynamic and biophysical models. Current inaccuracies of modelling include a tendency to underestimate non-farm DIN, which will lead to a tendency to over estimate farm effects.

IMTA

Further studies, including field trials at a meaningful scale are required to determine the ecological efficacy of IMTA practices that aim to recycle waste through a multi-trophic food chain on site.

Interactive management tools

Full utilisation of model results outside the scientific community requires the development of interactive management tools with a Graphic User Interface (GUI) to access to the full range of model results with a simple online query. Such models can then keep the industry, policy makers and interest groups informed in an accessible and concise way.

2.3. Filter feeders (green-lipped mussels and Pacific oysters)

The difference in the structures used to culture mussels and oysters demarcates the difference in the relative benthic impacts of each species on the environment (see Chapter 3), while pelagic impacts are less dictated by culture type. Mussels are suspended on rope droppers usually at depths of more than 20 metres whereas typically oysters are laid out on sticks, in mesh bags or trays across racks (0.3–1 metres high) that are fixed in the intertidal zone in estuaries and exposed during low tide (Forrest et al. 2007a). Pelagic environment impacts are categorised as:

- extraction of phytoplankton and organic particulates and changes in plankton species composition;
- dissolved nutrient and particulate release into the water column;
- provision of suspended surfaces allowing settlement of biofouling communities, which in turn have primary impacts on the water column (extraction and organic loading);
- translocation of diseases and invasive species;
- impact of farm structures on current velocities.

In this chapter the spatial extent of the impacts is considered at the farm scale while cumulative and wider ecological impacts are covered in Chapter 12.

2.3.1 Descriptions of main effects and their significance

2.3.1.1 Extraction of phytoplankton and organic particulates and changes in plankton species composition

Summary

The shellfish cultured in New Zealand, the green-lipped mussel (*Perna canaliculus*) and the Pacific oyster (*Crassostrea gigas*) filter large volumes of water from which they extract suspended particulate matter (SPM), phytoplankton, and in the case of mussels some auto and heterotrophic picoplankton and microzooplankton (Zeldis et al. 2004). The clearance rate (the volume of seawater filtered by an individual shellfish) can vary considerably according to body size and seston quantity and quality. Rates of up to 8.6 litres per hour have been reported for *Perna canaliculus* by James et al. (2001). If significant food depletion occurs, cultured mussels could theoretically

Table 2.4: Pelagic effects associated with extraction of phytoplankton and organic particulates and changes in plankton species composition from filter-feeder aquaculture operations.

Description of effect(s)	Through filtration of the water column, shellfish remove phytoplankton, some auto-trophic and heterotrophic picoplankton and microzooplankton, and suspended particulate matter (SPM) which could change plankton community structures and to reduce phytoplankton availability to other filter-feeding organisms.
Spatial scale	*Local* (within farm and the primary depletion footprint) – The scale is influenced by the carrying capacity and physical attributes of the site such as depth, topography, hydrodynamics, wind direction, upwelling/downwelling areas, ambient nutrients, SPM levels and natural variability in plankton concentrations.
Duration	*Short term* – Duration of the effect is dependent on farming intensity per unit of water volume, seasonal harvesting regimes, the natural variability in phytoplankton and local hydrodynamics (e.g. flushing rates).
Management options	At farm scale, management practices can alleviate excessive nutrient enrichment and plankton depletion. Compliance monitoring of the near-field water column for key plankton parameters (chl-a, abundance, species composition, DIN concentrations). Development and validation of models to predict plankton and SPM depletion inside a farm and within the primary footprint.
Knowledge gaps	Baseline data on size classes of phytoplankton to assess differential extraction. New studies are required to determine changes in water column variables due to shellfish aquaculture in areas such as shallow estuaries where oysters are grown on racks.

* Italicised text in this table is defined in chapter 1 – Introduction.

out-compete other suspension feeders (e.g. zooplankton and benthic shellfish) for particulate food, or exceed what is termed the ecological carrying capacity of a farmed area (Keeley et al. 2009).

Near-field depletion of plankton can be significant in sheltered bays. A GIS-based model coupled to two-dimensional hydrodynamic tidal simulation model indicated the likelihood of phytoplankton depletion in and around existing mussel farms in small dead-end embayments within larger bays in Pelorus Sounds, where clusters of small (less than two hectare) farms showed overlapping footprints at levels of 15 to 20 percent phytoplankton depletion 500 metres beyond the farm boundaries (e.g. Stenton-Dozey et al. 2006). However, tidal flushing rates appeared sufficient to replenish phytoplankton concentrations in these sheltered embayments.

A Fisheries Resource Impact Assessment (FRIA) became part of resource compliance for marine farms from 2004 in an effort to appraise existing farms before new aquaculture legislation was introduced in 2011. The FRIA process aimed to identify any undue adverse effects on wild fishery resources and species with conservation status. FRIA assessments of depletion footprints for large-scale mussel farms in the Firth of Thames (Stenton-Dozey et al. 2008) applied biophysical model simulations to identify depletion zones (Broekhuizen et al. 2004, 2005). These models are highly sophisticated, using field survey data for validation and taking into account the growth rates of phytoplankton, zooplankton and fish larvae (snapper in the Firth of Thames assessment), water column stratification, seasonal wind direction and tidal currents, as well as the physiological response of mussels to different food concentrations. The simulated effect was an increase in the depletion of SPM, phytoplankton and microzooplankton within the farm leases but not far beyond lease boundaries.

Mussels can most effectively extract particles within an approximate size range of 52–100 µm (Safi & Gibbs 2003), however, particles as large as 600 µm can be retained (Zeldis et al. 2004). This initial extraction can include phytoplankton, zooplankton (including copepods, fish and invertebrate eggs and larvae), protozoa, bacteria, detrital organic matter and inorganic sediment (Keeley et al. 2009). There has been speculation, but no direct evidence, that such extraction for extended periods could alter the species composition of the plankton in the medium to longer term. This speculation also considers the addition of a huge numbers of mussel larvae into the plankton community. Long-term monitoring of the pelagic environment around mussel farms in the Firth of Thames has, however, shown no changes in the relative proportion of diatoms, flagellates or ciliates over an eight year period (Stenton-Dozey et al. 2005; Zeldis 2008).

Unlike the extensive research on plankton depletion by suspended mussel culture, there are little data on the effects of oyster culture on the intertidal pelagic environment. In reviewing international literature on oyster culture, Keeley et al. (2009) made the observation 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 and normally contain significantly lower biomass per cubic metre than mussel farms.

Studies from overseas indicate that control of plankton biomass and composition by cultured oysters depends on oyster density as well as the flushing rate through racks. A study by Lin et al. (2009) using a mass-balance trophic model to predict temporal responses of community biomasses to the system-scale removal of oyster-culture racks from Tapong Bay (an euphotic lagoon system in Taiwan), showed that the biomasses of phytoplankton, herbivorous and carnivorous zooplankton and pelagic fish and soft-bottom fish increased. In Thau Lagoon, France, Chapelle et al. (2000) halved the oyster biomass in their model and found greater abundances of phytoplankton and zooplankton. However, in a model of Marennes-Oléron Bay in France, Leguerrier et al. (2004) manipulated the density of cultured oysters and found that primary and secondary production were enhanced by the presence of cultured oysters. They concluded that oyster culture had a small impact on the stability of their system, in which only 16 percent of the area was devoted to oyster farming. These studies indicate that top-down control of plankton by cultured oysters depends on oyster density as well as the flushing rate through racks. However, in relation to New Zealand there have been no such studies.

Table 2.5: Pelagic effects associated with dissolved nutrient and particulate release into the water column from filter-feeder aquaculture.

Description of effect(s)	Shellfish release dissolved nutrients (mainly ammonia) and organic particulates (faeces and pseudofaeces) into the water column. Potentially, this can lead to the nutrient enrichment of the surrounding water.
Spatial scale	Mainly *local* within a farm and the primary depletion footprint. The scale is dependent on flushing rates and subsequent dilution.
Duration	Duration of effect is variable depending on flushing rates, stocking densities and harvesting.
Management options	Compliance monitoring of the near-field water column for key plankton (Chl-a, phytoplankton and zooplankton species, suspended particulates) and nutrient parameters (dissolved C, N and P) as part of an adaptive management programme.
Knowledge gaps	Determination of carrying capacity of estuaries, harbours, embayments and coastal regions for shellfish farming, especially for oysters. Further development of mass balance models of nutrient loading (inorganic and organic) from all sources (natural and anthropogenic) that can be used to assess potential additions from shellfish. Development of hydrodynamic models to resolve the effects of tidal and wind-driven forcing and that reflect regional topography. New methods are required to quantify processes, such as flocculation and aggregation that affect dispersion of particulate matter from shellfish farm sites. New studies are required to determine changes in water column variables in areas of shellfish aquaculture, such as in shallow estuaries where oysters are grown on racks.

* Italicised text in this table is defined in chapter 1 – Introduction.

2.3.1.2 Dissolved nutrient and particulate release into the water column

Summary

During feeding, mussels and oysters excrete ammonia into the water column which is then oxidised through the activity of heterotrophic bacteria. Fouling organisms attached to mussel lines and oyster racks also add to the dissolved nitrogen pool raising above ambient levels in the water column. A further source of aquaculture-derived dissolved nitrogen can arise from benthic fluxes in which the microbial breakdown of mussel biodeposits on the sediment surface releases ammonium into the water column. In the New Zealand situation, where most shellfish farms are located in well-flushed areas, nutrient enrichment beyond the farm boundaries is difficult to detect (Zeldis 2008). Mixing and dispersion rapidly dilute farm by derived nutrients. In-farm nutrient enrichment could stimulate production of phytoplankton blooms and of algae attached to the farm structures (Black 2001). In the Pelorus Sounds, prolific growth of the Asian kelp *Undaria pinnatifida* occurs on suspended mussel lines (Keeley 2009). Its success could be derived from a combination of farm-derived nutrients and the opportunity to colonise suspended clean rope surfaces when mussel lines first enter the water.

Mussels and oysters release faeces and pseudofaeces into the water column and most of this material sinks to the seabed. However, a proportion becomes trapped in ropes or racks together with waste from fouling organisms and passing silt that has settled out of the surrounding water column. Remineralisation of this trapped material releases dissolved nutrients and organic particulates into the water column, especially during rough weather conditions and during harvesting. This can have a significant effect on water column turbidity and consequential shading of microphytobenthos. However, some of the SPM will be consumed by the mussels, some will settle to the seabed and a proportion will enter the wider environment. In well-flushed sites increased turbidity would only be intermittent.

Keeley et al. (2009) indicate that the effects of intertidal oyster farming on water quality in New Zealand estuaries appear to be unknown, but they suggest that significant degradation is highly unlikely to occur given the minor to moderate levels of seabed enrichment that have been documented (Forrest 1991; Forrest & Creese 2006). Adverse water quality effects from oyster farming and other forms of aquaculture are more likely where farms are over-stocked and located in poorly flushed environments (Wu et al. 1994; La Rosa et al. 2002). This can be avoided by appropriate site selection and by ensuring that farm structures are configured in a way that has a minimal effect on flushing processes.

2.3.1.3 Suspended surfaces provide for settlement of biofouling communities

Summary

Keeley et al. (2009) provide a comprehensive review of the settlement of biofouling communities on mussel farms and oyster racks and only a short summary is presented here. There is also extensive international literature on the functional role of different components of biofouling communities both on aquaculture and non-aquaculture structures that are important to consider when assessing pelagic effects (Sutherland 1978; Mazouni et al. 2001; Hughes et al. 2005; Cook et al. 2006; Greene & Grizzle 2007; McKindsey et al. 2007; Dijkstra et al. 2007; Dumbauld et al. 2009; Forrest et al. 2009; Lutz-Collins et al. 2009).

The dominant biota that settles on farm structures in New Zealand includes macroalgae (seaweeds) and sessile (attached) filter-feeding invertebrates such as sea squirts, bryozoans and mussels. These assemblages typically have a range of other non-sessile animals associated with them, such as polychaete worms and various small crustaceans. The functional role of the associated fouling community is not well understood, but it is likely to contribute in some way to the water column effects that are described above (extraction and loading).

Overseas studies show that the filtration capacity of extensive fouling communities has the potential to deplete phytoplankton and other particulates from the water column (Mazouni et al. 2001). In addition, biodeposits (i.e. faeces from consumed food and pseudofaeces from unprocessed food) produced by the fouling community, and inadvertent or deliberate removal of fouling biomass, have the potential to exacerbate seabed enrichment. Introducing significant quantities of artificial reef structures in the form of marine farms with the associated fouling assemblages are also thought to influence fish assemblages (see Chapter 6).

2.3.2 Impact mitigation and management strategies

2.3.2.1 Impact mitigation

Impact mitigation requires both good coastal planning and farm management at the local scale. If environmental impacts are minimised within a farm site or lease area, the spread of pelagic impacts can be contained. Refer to Section 2.2.3 for discussion of issues relating to regional management, use of models, monitoring and IMTA.

2.3.3 Knowledge gaps

2.3.3.1 Biophysical models

Current biophysical models are focused on lower trophic levels (Broekhuizen et al. 2004, 2005; Broekhuizen & Zeldis 2006). Further development is required to consider coupling to higher trophic levels, most notably fish that have been found to use farms as settlement sites for juveniles (Fernandez-Jover et al. 2009), as well as capitalising on the ecosystem changes near the cages (Dempster et al. 2002) and at a regional level (Machias et al. 2005). In addition, further studies are required to determine whether the extents of far-field effects on food

Table 2.6: Pelagic effects associated with biofouling communities due to filter-feeder aquaculture operations.

Description of effect(s)	Suspended or elevated structures provide a novel "suspended" habitat in the water column that provides a settlement surface for passing invertebrate larvae and algal spores. Biofoulers present an additional source of nutrient and organic particle loading into the pelagic environment while the filter feeders within the biofouling community add to the extraction of plankton.
Scale	Mainly *local*.
Duration	Duration of effect equals duration of farm existence.
Management options	At farm scale, management practices reduce the amount of biofouling on the ropes. Physical removal of biofoulers during reseeding of ropes or cleaning of oyster bags and/or cages. Seeding of ropes can be timed to exclude periods when the most common biofoulers, larvae and spores (e.g. ascidians and *Undaria*) are abundant in the water column.
Knowledge gaps	Research on the functional groups within a biofouling community to quantify their role in food extraction from, and nutrient loading into, the pelagic environment. An understanding of biofouling colonisation rate and sequence onto suspended structures.

* Italicised text in this table is defined in chapter 1 – Introduction.

webs (particularly in nutrient-driven systems) are accurately predicted from the existing models.

For information on management gaps relating to hydrodynamic models, model calibration, IMTA and interactive management tools please see section 2.2.4.2.

2.4 Lower trophic level species

2.4.1 Overview of pelagic effects

The two lower-trophic level species that have the most imminent potential for aquaculture development in New Zealand are the sea cucumber *Australostichopus mollis* and the macroalga, *Undaria pinnatifida*.

Sea cucumbers are found on the seabed and feed on organic matter, and recent research has shown that they are attracted to the deposited farm waste under mussel lines (Davey et al. in prep). The potential for the aquaculture development of *A. mollis* has been recognised in a number of publications; with potential for benthic on-growing under mussel farms (Slater 2006; Slater & Carton 2007; 2010; Slater et al. 2009, 2010; MacTavish 2010) and land-based hatchery (Stenton-Dozey & Heath 2009). The future assessment of pelagic effects from sea cucumber farming will depend on the sea-based method of farming. Juveniles grown on the seabed in cages under mussel farms have shown good growth rates (Slater 2006) as well having as a significant impact on removing mussel biodeposits (MacTavish 2010). In Canada, trials are under way on sea cucumbers together with other species in reef cages in close proximity to salmon farms (G. Reid pers. comm.).

U. pinnatifida, an invasive species from Japan, grows prolifically on mussel farm backbones and droppers and can also be found around salmon cages especially on the anchor warps. There has been trial culture of a number of seaweeds in New Zealand (*Porphyra* and *Ecklonia radiata*) (NIWA data). Although the potential to grow *Undaria* commercially has been recognised for a long time, until recently this has not been possible due to it being classified as an invasive species. Farming of *Undaria* is now allowed in selected heavily infested areas with permission from MPI.

2.4.1.1 Sea cucumbers

Summary

Resuspension of faeces from sea cucumbers on the seabed can impact the water column, increasing the organic particulates in suspension and stimulating bacterial activity. If sea cucumbers are grown in suspended cages, the food source would be settled seston on the cage surfaces (especially under existing salmon or mussel farms). This can lead to removal of farm organic waste, but at the same time natural seston material will also be consumed.

In Australia, sea cucumber ranching has been considered in the Northern Territories (Northern Territory Government 2004). In this discussion document, genetic drift, translocation of associated species and effects on endemic species were identified as potential cumulative effects of sea cucumber ranching, but no specifically pelagic effects were identified.

Table 2.7: Pelagic effects associated with sea cucumber aquaculture.

Description of effect(s)	Resuspension of sea cucumber faeces can impact the near-bottom pelagic zone by increasing suspended particulates. Bioturbation of benthic sediments by dense stocking of sea cucumbers could lead to changes (adverse or beneficial) to benthic–pelagic biogeochemical fluxes.
Scale	Mainly *local*.
Duration	Duration of effect equals duration of farm existence.
Management options	Free ranching or cage culture. Farm sea cucumbers within an IMTA design.
Knowledge gaps	Research the impact of sea cucumbers on the near-bottom pelagic environment. Research the best farming practice to mitigate impacts by comparing free ranching with benthic or suspended cage culture or within an IMTA design. Determine the role sea cucumbers can play in mitigating impacts within an IMTA operation.

* Italicised text in this table is defined in chapter 1 – Introduction.

2.4.1.2 *Undaria*

Table 2.8: Pelagic effects associated with *Undaria* aquaculture

Description of effect(s)	Nutrient extraction (nitrates, phosphates, silicon) can reduce nutrient availability to natural phytoplankton populations and other algae species. Shading of the water column and thus impacting light penetration to benthic algae.
Scale	Mainly *local* but potential to be *regional* if stocking density is high.
Duration	Duration of effect equals duration of farm existence.
Management options	Balance seaweed production with natural nutrient availability for production. Do not overstock to prevent reduction in light penetration. Culture seaweed together with finfish in an IMTA design.
Knowledge gaps	Research the impact of seaweed culture on the pelagic environment. Research best farm structures to outgrow seaweeds and reduce impacts. Research the best farming practice to mitigate impacts growing in an IMTA design.

* Italicised text in this table is defined in chapter 1 – Introduction.

Summary

Due to the lack of commercial production, the pelagic effects of seaweed culture in New Zealand are undetermined. However, there is a growing body of international literature on the ecological effects of seaweed culture (see UNDP/FAO 1989; Phillips 1990). Nutrient extraction with a knock-on effect of reduced production of phytoplankton based on competition is listed as the only potential pelagic impact.

IMTA

The area below seaweed culture areas can be used very positively for production of other aquatic animals. For example, farms in the Republic of Korea, Japan and China find that the benthic area below seaweed farms can be used for culturing invertebrates, such as abalone or sea cucumber, thus maximising the production and profit per unit area (Phillips 1990). *Undaria* and sea cucumbers have significant potential for co-culture with finfish farms within an IMTA operation in New Zealand (see Figure 2.1) where the food source for each comes partially from existing finfish waste (DIN and organic particulates). This can potentially mitigate some of the possible environmental impacts of sea-based finfish culture.

Refer to Section 2.2.3.1 for details on IMTA designs.

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