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Comparison of the international regulations and best management practices for marine finfish farming

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Executive summary

Successful marine finfish aquaculture in New Zealand requires the balancing of economic productivity, environmental stewardship, and social expectations of our country. Minimising the environmental impacts of marine aquaculture should be a common goal for regulatory authorities and producers because environmental quality, growth and health of fish, and farms profits are intimately linked. Internationally, many countries and independent global organisations have developed aquaculture best management practices to improve the environmental and financial performance of aquaculture operations. The aim of this project is to compare the international regulatory objectives, statutory regulations and best management practices for marine finfish farming in New Zealand with other countries (Norway, Scotland, Canada, USA and Australia) that have similar environmental standards to New Zealand, and to develop a list of potential operational changes for New Zealand finfish farms that may be helpful in improving the financial and/or environmental performance of finfish aquaculture in New Zealand.

A review of the aquaculture legislation and regulations in Norway, Canada, Scotland, USA, Australia and New Zealand show that:

1. Aquaculture is typically regulated by many acts involving different levels of government and many regulatory authorities, and consequently, approval of a new aquaculture development is an expensive and lengthy exercise. The lack of a streamlined application process is particularly a problem in Scotland, Canada and the USA.

2. Many countries are struggling to balance the growth of viable aquaculture industries with the issues of environmental protection and social expectations for the use of water space. This is particularly an issue in New Zealand, where the limits on access to appropriate water space for aquaculture has impeded implementation of recognised best management practices and limited expansion of the aquaculture industry. There is considerable public consultation of individual aquaculture resource consents in New Zealand, which also results in lengthy (and costly) delays to the producer.

3. In Australia and Scotland the government is required to create marine development plans where aquaculture is permitted. This greatly reduces the time and cost required for new aquaculture applications (within permitted areas) because environmental impact assessments and public consultation requirements of new farms are greatly reduced.

4. New Zealand is the only country that does not have legislated aquaculture monitoring requirements and regulations on permitted environmental standards. Creation of aquaculture regulations is likely to remove inconsistencies in environmental standards and enable better enforcement of environmental standards.

5. Environmental impact in North America is primarily assessed by chemical measures e.g. free sulfides and redox potential, which have been validated as proxy measures of ecological benthic impact. The use of chemical measures provides a non-subjective assessment, reduces compliance costs and allows for greater spatial replication, which will improve far-field assessment and forecasting.

6. Countries are confronting the same environmental issues including organic waste production, disease, use of therapeutic agents and chemicals, escapes of aquaculture stock, bio-fouling management and sustainability of feed ingredients. Modelling

studies that are verified by long-term environmental data sets are required to address the increasing concern about far-field and cumulative effects of aquaculture.

Comparison of the salmon farming operational practices in New Zealand with international best management practices using a case study of the New Zealand King Salmon Company has identified a number of areas where finfish aquaculture in New Zealand could potentially be improved:

1. **Farm location—**A number of current finfish farms are situated in sub-optimal locations, which results in poor fish performance and higher environmental impact. Consideration should be given to relocate these farms to more suitable environments (sheltered with high water velocities, >40 m deep and <17 °C).

2. **Net design and arrangement—**Changes to net size and arrangement should be considered to maximise water flow through the nets, particularly in sheltered locations. Small net-pens should be replaced with larger net-pens, arrays of multiple net-pens should be replaced with individual net-pens in staggered rows, and rows of net-pens should be positioned with the longest axis perpendicular to the current.

3. **Environmental management—**Implementation of fallowing between production cycles (3–24 months) combined with site rotation will allow partial remediation of sites and prevent cumulative degradation of the environment. Implementation of fallowing and site rotation will require additional water space if current production levels are to be maintained.

4. **Bio-fouling management—**Nets in low-flow environments should not be cleaned *in situ* but removed and cleaned on land. Nets need to be cleaned sufficiently frequently so that bio-fouling rates do not decrease water flow and dissolved oxygen concentrations inside the nets. Dissolved oxygen concentrations should be ≥70% saturation inside the net-pens.

5. **Fish health management—**Where infectious disease risk can be demonstrated, single-year class production should be carried out at all sites with a short fallow period (1–3 months) between production cycles to limit disease transmission. Sites within close proximity of one another should stock the same year class. Emergency aquaculture sites should be created for use when required e.g. during harmful algae blooms.

Many of these suggested improvements require changes at both the governmental level and the operational level. The lack of suitable water space available for aquaculture and the restrictions of current resource consent conditions have limited the uptake of best management practices such as site rotation, fallowing and optimal net-pen arrangements. Based on overseas examples, implementation of these best management practices will improve the economic and environmental performance of finfish aquaculture in New Zealand, facilitating the sustainable growth of New Zealand's aquaculture industry.

1 Introduction

Environmental quality, growth and health of fish, and farms profits are intimately linked. Numerous studies have now demonstrated that localised environmental degradation resulting from poor farm management directly impacts the growth and health of fish (e.g. Black *et al.*, 1996; Belle & Nash, 2008; Burt *et al.*, 2012; Remen *et al.*, 2012). Better farm efficiency and higher profits are good incentives for producers to minimise the environmental impacts of aquaculture and maintain a healthy culture environment. Thus, minimising the environmental impacts of marine aquaculture should be a common goal for regulatory authorities and producers. The general environmental impacts of marine finfish farming are similar (e.g. organic enrichment of sediment sometimes developing into anoxic conditions, changes in the benthic macrofauna composition, and the accumulation of metals, chemicals and therapeutants in the water and sediment), although the magnitude of the impacts will vary among sites and with culture species, because of differences in hydrodynamics, topography, local environmental conditions and species requirements. Much research has now been conducted on the environmental impacts of finfish farms and methods of minimising the impacts of finfish farming on the environment (for reviews see Scottish Association for Marine Science & Napier University, 2002; FAO, 2009). Some of these methods are regulated through legislation, whereas other methods are instigated by producers at the farm operational level. The aim of this report is to compare the international regulatory objectives, statutory regulations and best management practices (BMP) for marine finfish farming in New Zealand with other countries (Australia, Canada, USA, Norway and Scotland) that have similar environmental standards to New Zealand, and to develop a list of potential operational changes for New Zealand finfish farms that may be helpful in improving the financial and/or environmental performance of finfish aquaculture in New Zealand.

This report does not review all the BMP and regulations of finfish farms. It is specifically focused on BMP and regulations that have an impact on farm productivity, such as BMP that increase the growth and survival of fish by improving environmental conditions, increasing feed conversion ratios (FCR), and reducing losses from disease, predation and escapes. While important, the BMP and regulations around maritime safety, social impacts, food safety, sustainability of feed ingredients, energy efficiency and employment are not reviewed in this report. The scope of the report is limited to marine finfish farms and salmon is used as a reference species because salmonids account for around 66% of the global net-pen finfish production and marine salmon culture occurs in all six countries reviewed (Tacon & Halwart, 2007). However, many of the recommendations are likely to be relevant to farming other fish species in New Zealand.

2 Comparison of international regulatory objectives, statutory regulations, and BMP for finfish farming

The regulation of aquaculture is the most established in Canada, Australia, New Zealand, Norway, Scotland and some states of the US (FAO, 2009), and thus, this review is limited to these countries. In Canada, Australia and the US, aquaculture regulations differ among states/provinces. All six countries produce marine farmed salmon and this report focuses on the main salmon growing jurisdictions in these countries, to enable comparisons between farming operations that have similar species requirements. Three species of salmon are farmed globally, Atlantic salmon (*Salmo salar*), Chinook salmon (*Oncorhynchus tshawytscha*) and Coho salmon (*Oncorhynchus kisutch*). Global salmon production was ~1,577,000 t in 2010, of which, 90% was Atlantic salmon (FAO Fisheries Department, 2013). It should be noted that while the vast majority of literature reviewed in this report is from Atlantic salmon, New Zealand only produces Chinook salmon, and species-specific differences may exist. For example, Chinook salmon have a much higher oxygen requirement than Atlantic salmon (Trudel *et al.*, 2004; Enders & Scruton, 2005).

2.1 OVERVIEW OF AQUACULTURE REGULATION BY COUNTRY

2.1.1 Norway

Net-pen aquaculture was pioneered in Norway in the 1970s for the cultivation of salmon (Tacon & Halwart, 2007) and the country is the world's leading producer of cultured salmon, with over 1000 marine salmon farming sites and over 1 million tonnes of Atlantic salmon cultured in 2010 (Directorate of Fisheries, 2012; FAO Fisheries Department, 2013). Finfish farming in Norway is regulated by the Aquaculture Act (2005) (Norway), which aims to *"to promote the profitability and competitiveness of the aquaculture industry within the framework of a sustainable development and contribute to the creation of value on the coast."* The Aquaculture Act (2005) (Norway) focuses on the growth and innovation of the aquaculture industry, simplification of the approval process, protection of the environment, and consideration of other users of the coastal zone (Norwegian Ministry of Fisheries and Coastal Affairs, 2005). New aquaculture applications are made to the Directorate of the Regional Fisheries Office, which, upon approval, sends the application out to various other regional authorities[1] for approval (Norwegian Ministry of Fisheries and Coastal Affairs, 2005). An Environmental Impacts Assessment (EIA) is required prior to the approval of new large farms[2], and compliance with BMP tends to be regulatory (Belle & Nash, 2008). Several regulations govern the operation of finfish farms (see Directorate of Fisheries, 2013). Aquaculture regulation in Norway is very focused on equipment specifications (Belle & Nash, 2008), and net-pen construction and mooring systems are standardised in the Regulation on Technical Standards for Equipment used in Farming Operations (NYTEK) (2004) (Norway).

Environmental monitoring requirements are set at a local and a regional scale. Local environmental monitoring requirements are based on the level of impact and exploitation of the site, whereas, regional environmental monitoring requirements are set at the discretion of the local authority (Wilson *et al.*, 2009). Environmental monitoring in Norway is primarily

[1] The County Governor, the Norwegian National Coastal Administration, the Norwegian Food Safety Authority, Municipality, and the Norwegian Water Resources and Energy Directorate.
[2] ≥48,000 m^3 for movable pens or ≥36,000 m^3 for permanently fixed pens.

based on the accumulation of organic matter. The level of accumulation on each farm is modelled through a 'Modelling – On-growing Fish Farm – Monitoring' (MOM) system. Farms that have the lowest level of impact are not required to conduct any environmental monitoring, whereas farms with the highest level of impact must have a comprehensive environmental assessment that is conducted by specialists in benthic fauna (Holm *et al.*, 2003; Grøttum & Beveridge, 2007). Previously, farms that did not meet environmental standards were allowed to move the farm to a different location, but this is rarely the case now, instead they must either lower production levels or allow the site to fallow (Wilson *et al.*, 2009).

2.1.2 Scotland

Scotland produces ~90% of the United Kingdom's finfish production (Wilson *et al.*, 2009), with ~158,000 t of Atlantic salmon produced in 2010 across 254 active sites (Walker *et al.*, 2012). Governance of aquaculture in Scotland is complex, with over 60 pieces of relevant legislation and 10 different statutory authorities (Scott, 2010). Scotland has a separate legal system from the rest of the United Kingdom, with aquaculture in Scotland governed by two main acts; the Marine Act (2010) (Scotland), and the Aquaculture and Fisheries Act (2007) (Scotland). The main points of the Marine Act (2010) relevant to aquaculture are: 1) a statutory requirement to develop regional marine plans that will facilitate the sustainable management of the marine area (currently under development), and 2) a simplified licensing system that will allow aquaculture consents to be granted by regional authorities or the government. The Aquaculture and Fisheries Act (2007) provides legislation around the record keeping required by producers, management of parasite infestations, and the prevention of fish escapes. Currently, a new Aquaculture and Fisheries Bill (2012) (Scotland) is being considered by parliament. If accepted, the new act would require farmers to comply with: farm management area (FMA) practices if the farm is located within a FMA; equipment specifications for net and mooring design, construction and maintenance; and controls to prevent the spread of commercially damaging species.

The Scottish Government supports the aquaculture industry's target for sustainable growth of aquaculture, with a targeted increase of 32% in the number of marine farms since 2011 (The Scottish Government, 2013). The government has also recently developed a Strategic Framework for Aquaculture, which has five main goals; healthier fish and shellfish; improved systems for licensing aquaculture developments, improved containment, better marketing and improved image, and improved access to finance (Marine Scotland, 2009).

Approval of new large finfish farms (>100 t yr^{-1}, or >1000 m^2) or farms located in a sensitive habitat requires an EIA. Regional and National Marine Plans are currently being development under the Marine Act (2010) (Scotland). In the interim, the government has issued guidelines for the location of marine farms (Marine Scotland, 2013). Coastal areas are categorised based on their environmental sensitivity, which provides farmers with an estimated probability of getting a marine farm approved in particular areas. New farms also require licences from a number of authorities: a planning consent must be obtained from the local authority; a discharge consent and medication consent from the Scottish Environmental Protection Agency (SEPA); a navigation consent from Marine Scotland; and a seabed lease from the Crown Estate (Scott, 2010). Compliance with environmental monitoring requirements are assessed by SEPA, which permits a relatively limited level of environmental impact (Table 4) (Wilson *et al.*, 2009).

Management of disease and parasitic infections is a major focus of Scottish aquaculture legislation, with regular monitoring for parasites and diseases (particularly Infectious Salmon Anaemia (ISA) and the ectoparasite, *Gyrodactylus salaris)* conducted by the Fish Health Inspectorate (FHI). The FHI provides a free disease diagnostic service for farmers, and has the power to prevent movement of diseased stock, specify control measures, or order the culling of diseased stock (The Scottish Government, 2013).

2.1.3 Canada

Around 310 km^2 of water space is license for marine finfish farming in Canada (OCAD, 2003). The country is the fourth largest salmon producing country in the world, with ~100,000 t produced in 2010 (FAO Fisheries Department, 2013). Atlantic salmon is the main farmed species, but small quantities of Chinook and Coho salmon are also cultured. Salmon farming started in Canada in the 1970s and marine culture of salmon predominantly occurs in British Columbia (74%), New Brunswick and Nova Scotia (FAO, 2012).

Aquaculture in Canada is governed at both the federal and provincial level and is regulated by several pieces of legislation. At the federal level, aquaculture is governed by the: Fisheries Act (1985) (Canada) and the Species at Risk Act (2002) (Canada), which protects wild species and their habitats; and the Navigable Waters Protection Act (1985) (Canada), which governs maritime safely issues. Prior to 2012, the majority of new aquaculture developments were required to conduct an EIA[3] under the Canadian Environmental Assessment Act (1992) before gaining approval for an aquaculture development. However, amendment of the Canadian Environment Assessment Act (2012) removed the requirement for an EIA for aquaculture developments by the federal government. EIAs for aquaculture developments may still be required at the discretion of provincial governments (Nova Scotia Fisheries and Aquaculture, 2013) but the conditions for requiring an EIA under provincial governments are currently unclear (Butler, 2013).

Prior to 2012, the federal Fisheries Act (1985) (Canada) primarily focused on any “harmful alteration, disruption or destruction of fish habitat”. This historic legislation only considered the local and small-scale effects, which could be practically monitored and used as proxy measures for large-scale effects. The unintended consequence of focusing on the fine-scale measures was the loss of a higher level, large-scale perspective. In short, assessment of near-field effects was over-emphasised, in part because near-field effects are easier to assess than far-field effects. Furthermore, the uncertainty of finding ecologically meaningful far-field effects has been an effective deterrent to researchers wanting to publish significant findings. A review of the regulatory framework in 2012 has led to changes which place far-field effects at the fore. The regulatory objective is now to control any serious harm to a fishery (with fishery being defined to include an existing aquaculture activity or anything which is caught under licence (commercial, recreational or aboriginal)). Assessing ‘serious harm’ requires the analysis of the activity to consider both the pathways and the scale of effect.

Hargrave (2002) developed a ‘Decision Support System’ (DSS) to assess potential far-field and near-field effects of new aquaculture developments, and to reduce the subjectivity and inconsistency among environmental assessments. The DSS is currently used in Canada and consists of a series of questions concerning far-field and near-field impacts (Table A in Appendix). Based on the final cumulative score, aquaculture applications are ranked as acceptable, provisionally acceptable or unacceptable. The DSS does not quantify far-field impacts but only assumes that they exist and seeks to distance fish farms from any features that may be adversely affected by the farm. It also does not quantify the potential cumulative effects of farms on the environment i.e. whether an existing environment under stress could assimilate an additional waste burden.

Subsequent to gaining approval, new aquaculture developments must obtain an operating licence from the appropriate provincial government. The provincial government is also responsible for conducting site inspections and ensuring compliance with both federal and

[3] Known as an Environmental Assessment (EA) in Canada. For consistency, it is referred to as an EIA in this report.

provincial regulations (Wilson *et al.*, 2009). In British Columbia, aquaculture waste is regulated by the Finfish Aquaculture Waste Control Regulation (2003) (BC), which requires farmers to monitor the environment and comply with environmental standards. The concentration of free sulfide in the sediment and macrobenthic community abundance and richness are the main methods of assessing environmental impact (Table 4). Producers are also required by law to implement a BMP that aims to continually minimise environmental impact and reduce waste generated by the farm. Monitoring requirements and environmental standards are much higher in British Columbia than the other provinces, and non-compliance consequences are more stringent. Farms that exceed environmental thresholds are not allowed to re-stock until the environmental parameter falls below the threshold (Wilson *et al.*, 2009).

In New Brunswick, the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick (NBEMP) stipulates the environmental monitoring requirements and BMP (Government of New Brunswick, 2006). NBEMP is enforced through the Clean Environment Act (1973) (New Brunswick). In Nova Scotia, aquaculture is regulated by the Nova Scotia Aquaculture Environmental Monitoring Program (NSEMP), which is enforced through the Fisheries and Coastal Resources Act (1996) (Nova Scotia). The NSEMP aims to examine the long-term relationship between aquaculture and the marine environment at a regional scale, and stipulates environmental monitoring requirements and BMP (Nova Scotia Fisheries and Aquaculture, 2011). The NBEMP and the NSEMP share the same BMP, which contains a tiered action plan. Environmental monitoring requirements and required mitigation measures are based on the level of oxygenation and free sulfides under the farm. Farms that are oxic (<1500 µM sulfide) have much lower monitoring and/or mitigation requirements than farms that are hypoxic (1500–6000 µM sulfide) or anoxic (>6000 µM sulfide) (Government of New Brunswick, 2006). In both provinces, compliance with the prescribed BMP is a requirement of the aquaculture licence.

2.1.4 USA

Aquaculture of Atlantic salmon in the USA began in the 1970s and current marine production is around 20,000 t per annum (FAO Fisheries Department, 2013).The majority of marine salmon farming in the USA occurs in Maine and Washington, and therefore, comparisons of aquaculture regulations are limited to these two states. Aquaculture producers in the USA are required to comply with federal, state and local government legislation. At the federal level, the National Environmental Policy Act (1969) (USA) requires that decisions on aquaculture developments are made with full consideration of the impact to the natural and human environment. Under this act, aquaculture developments are assessed as to whether they require a full EIA[4]. Co-ordination of the EIA system is the responsibility of state governments and the EIA requirements varies among states. New aquaculture developments must also acquire up to 14 permits from various regulatory authorities, depending on the state (Wilson *et al.*, 2009). Discharge of aquaculture waste is governed by the Clean Water Act (1972) (USA), which is regulated through a permit process that is administered at the state level. Under the Clean Water Act (1972) (USA), all farms that produce >45 t of finfish per annum are subjected to Effluent Limitation Guidelines (EPA, 2012) and must develop and comply with BMP detailing how the Effluent Limitation Guidelines are to be achieved.

In Maine, aquaculture is regulated by the Aquaculture Lease Regulations (1983) (Maine), which stipulate lease conditions and required baseline environmental monitoring data. Application for an aquaculture lease typically takes more than 8 months because of an extensive public consultation process (Maine Department of Marine Resources, 2013a). Finfish farmers must also obtain a discharge permit from the Maine Department of Environmental Protection, which stipulates numerous conditions regarding the discharge of

[4] Known as an Environmental Impact Statement (EIS) in the USA. For consistency, it is referred to as an EIA in this report.

feed, fish faeces, chemicals and therapeutants and escaped fish (see Tables 1–8 and State of Maine Department of Environmental Protection, 2008).

Aquaculture in Washington is regulated by numerous state and county authorities. Finfish farmers must obtain an aquaculture lease from the Washington Department of Natural Resources, and permits from: 1) the Washington State Department of Ecology, which manage the environmental impact of aquaculture operations and water discharge permits; 2) the Washington Department of Fish and Wildlife, which manage disease control and escapes in farmed fish, and protects wild species and their habitats; and 3) local county authorities, which manage shoreline development and considers the needs of other users of the marine space (Amos & Appleby, 1999; Aarset, 2002; Wilson *et al.*, 2009).

Environmental impact in the USA is primarily assessed by chemical measures. There is a strong trend in North America towards using chemical measures (both in water and sediments) as proxy indicators of ecosystem effect, and away from direct measurements of faunal abundance and biodiversity. Chemical measures are non-subjective and are cheaper to obtain, allowing for greater spatial replication. Due to the patchy distribution of materials derived from the aquaculture facility, increasing the intensity of sampling with validated proxy measures (such as sulphides or redox potential) reduces compliance costs and provides for improved far-field assessment and forecasting.

2.1.5 Australia

Salmon farming started in Australia in the 1980s in Tasmania and currently ~32,000 t of Atlantic salmon is cultured per year (FAO, 2005b; FAO Fisheries Department, 2013). Aquaculture producers in Australia must comply with federal, state/territory and local government legislation. Aquaculture is most regulated in South Australia and Tasmania (Productivity Commission, 2004), which are also the only two states that produce marine farmed salmon (Primary Industries and Resources South Australia, 2002), and therefore, review of state legislation is restricted to these two states.

State/territory governments are primarily responsible for aquaculture regulation and compliance (Productivity Commission, 2004). Aquaculture regulation in South Australia and Tasmania is based on a three-tiered approach involving: 1) resource assessment, planning and the creation of aquaculture zones; 2) allocation of aquaculture leases that provide long-term tenure within an aquaculture zone; and 3) administration of various licences and permits (Productivity Commission, 2004). In addition, approval from the federal government may be required under the Environment Protection and Biodiversity Conservation Act (1999) (Australia) for aquaculture activities that are likely to have a significant impact on a matter of national environmental significance. Aquaculture operations in South Australia and Tasmania typically do not require discrete environmental approvals, because of the mandatory aquaculture zone plans. However, an EIA is required in Tasmania for farms with a production of >100 t yr^{-1} (Productivity Commission, 2004).

In South Australia, aquaculture is governed by the Aquaculture Act (2001) (S. Australia), which has the objective *"to promote ecologically sustainable development of marine and inland aquaculture; maximise benefits to the community from the state's aquaculture resources; and ensure the efficient and effective regulation of the aquaculture industry."* This act requires that marine aquaculture plans are developed by the state government, which designate certain areas where marine farming is permitted[5]. Aquaculture leases cannot be issued outside of aquaculture-zoned areas. Environmental monitoring and reporting requirements are governed by the Aquaculture Regulations (2005) (S. Australia).

[5] Aquaculture zones; prospective aquaculture zones where experimental aquaculture is allowed for a maximum of three years; and aquaculture emergency zones, for emergency relocation of aquaculture operations.

In Tasmania, aquaculture is governed by the Marine Farming Planning Act (1995) (Tasmania) and the Living Marine Resources Management Act (1995) (Tasmania). The objectives of the Marine Farming Planning Act (1995) (Tasmania) are *"to achieve well-planned sustainable development of marine farming activities having regard to the need to integrate marine farming activities with other marine uses; minimise any adverse impact of marine farming activities; set aside areas for other activities; and take account of land uses and the community's right to have an interest in marine farming activities."* The act requires that marine farming plans are developed by the state government, which designate certain areas where marine farming is permitted[6] and stipulates management control measures. Environmental impact assessments and public consultation occurs when new marine farming plans are developed. Subsequent public consultation for new aquaculture developments within permitted areas is limited (Bartholomew, 2013). Tasmania has extensive environmental monitoring and compliance requirements for finfish farms (see Tables 1–8 and Woods *et al.*, 2004). Regulation of the environmental impacts of aquaculture are also governed by the Living Marine Resources Management Act (1995) (Tasmania), which has the objectives to "*achieve sustainable development of living marine resources having regard to the need to increase the community's understanding of the integrity of the ecosystem upon which fisheries depend; provide and maintain sustainability of living marine resources; and take account of the community's needs and interests in respect of living marine resources*". The act protects the environment and ensures that all users of the marine environment have fair access to its resources.

2.1.6 New Zealand

New Zealand differs from the other countries reviewed in that it cultures Chinook salmon rather than Atlantic salmon. In 2011, New Zealand produced around 14,000 t of Chinook salmon, which comprised around 50% of the global production of Chinook salmon (New Zealand Salmon Farmers Association Inc., 2011; Gillard, 2012). Salmon farming in New Zealand started in the 1970s and the two main producing regions are Marlborough Sounds and Stewart Island (see Section 4 for more information on salmon farming in NZ). The current surface area of marine farming structures in New Zealand is less than 0.1 km^2 (10 ha) (Rimmer & Ponia, 2007).

Aquaculture in New Zealand is governed by the Resource Management Act (1991) (NZ) and the Aquaculture Reform (Repeals and Transitional Provisions) Amendment Act (2011) (NZ). Prior to 2004, obtaining permission for new aquaculture space in New Zealand was a two-step process with producers needing to gain a resource consent from the local regional council and a marine farming permit from the Ministry of Fisheries. This process lacked clarity and resulted in significant delays in the consent process. In 2004, the introduction of the Aquaculture Reform Act (2004) (NZ) created a single, clearer process for granting aquaculture consents, and aimed to *"...enable the sustainable growth of aquaculture and ensure the cumulative environmental effects are properly managed while not undermining the fisheries regime or Treaty of Waitangi settlements"* (Aquaculture Reform Bill, 2004). The Aquaculture Reform Act (2004) stipulated that finfish farms were only permitted in Aquaculture Management Areas (AMA) that were designated by local regional councils (Wilson *et al.*, 2009). However, the creation of AMA was found to be a complex, expensive and time-consuming process, and very little new water space was made available for aquaculture (Ministry of Fisheries, 2011). In 2011 the Aquaculture Reform Act (2004) was amended to streamline the process of granting new aquaculture space. The main change of the Aquaculture Reform (Repeals and Transitional Provisions) Amendment Act (2011) is the removal of the requirement for farms to be located in designated AMA. Furthermore,

[6] Aquaculture zones and emergency aquaculture zones.

applications can be made to the Environmental Protection Authority (EPA) for plan changes and con-current resource consents if producers wish to locate farms in areas prohibited by coastal management plans.

The Resource Management Act (1991) requires all new aquaculture developments to submit an EIA[7] and obtain a resource consent/coastal permit from the appropriate regional council or unitary authority. Obtaining a resource consent for aquaculture in New Zealand can be an expensive and lengthy process because new aquaculture applications are subject to considerable public consultation, which significantly increases the time and cost required. For example, in a recent NZKS application for new farm space, there was 1272 submissions and 181 witnesses/submitters at the hearing (Bartholomew, 2013). Once a resource consent has been granted, the Ministry for Primary Industries (MPI) assesses the proposed development and needs to confirm that the development will have no 'Undue Adverse Effects' on recreational, customary or commercial fishing. If the proposed development is found to have an Undue Adverse Effect then compensation to the affected parties is required. Farmers must also register as a fish farmer with the MPI (Fisheries Amendment Act, 2011 (NZ); Ministry for Primary Industries, 2013). Currently, there are no coastal occupancy or lease charges for aquaculture sites.

Individual resource consents stipulate the location and scale of the farm, production limits and environmental monitoring and compliance standards. New Zealand does not have a set of generic regulations and standards for the environmental monitoring of aquaculture. Instead monitoring and compliance requirements differ for every site, depending on local regional council regulations and resource consent conditions. Older farm sites have very few environmental monitoring requirements, whereas newer farm sites have extensive monitoring and compliance regulations (M. Gillard, NZKS, pers. comm.). Some of the environmental standards stipulated in resource consents are based on the Australian and New Zealand Environment Conservation Council (ANZECC) guidelines (ANZECC, 2000) (e.g. zinc and copper thresholds), whereas other standards used are specific to the regional council. The local regional council is responsible for ensuring compliance with resource consent conditions (Wilson *et al.*, 2009; Ministry for Primary Industries, 2013).

The New Zealand Salmon Farmers Association Inc. (NZSFA) has developed an Environmental Code of Practice for the industry, and all members of the NZSFA agree to comply with the Code of Practice (NZ Salmon Farmers Association Inc, 2009).

2.1.7 Voluntary global BMP standards

Producers may also elect to comply with global BMP standards issued by international organisations such as the Global Aquaculture Alliance (GAA) or the Aquaculture Stewardship Council (ASC). Both the GAA and the ASC have published specific BMP standards for salmon (GAA, 2011; ASC, 2012). The goal of these BMP standards *"is to credibly offer measurable, performance-based requirements that minimize or eliminate the key negative environmental and social impacts of salmon farming, while permitting the industry to remain economically viable"* (ASC, 2012). Producers wanting to obtain the relevant certification are required to comply with numerous standards that cover environmental impacts, fish health and disease management, sustainability of feed ingredients, wildlife management, employee safety and working conditions, transgenic animals, escapes, energy efficiency and biosecurity, as well as the mandatory regulations required by their country's government. These voluntary BMP standards typically have higher requirements than legislated regulations, but the extra compliance costs involved may be offset by increased production through the reduction of mortality from disease and stress, and increased growth under better environmental conditions (Stewart, 1998; Backman *et al.*,

[7] Known as an Assessment of Environmental Effects (AEE) in New Zealand. For consistency, it is referred to as an EIA in this report.

2009). BMP certified products also have greater market access and can obtain a higher market price (ASC, 2013).

In summary, a review of the aquaculture regulations in Norway, Canada, Scotland, USA, Australia and New Zealand show that:

1. Aquaculture is typically regulated by many acts involving different levels of government and many regulatory authorities, and consequently, approval of a new aquaculture development is an expensive and lengthy exercise (OCAD, 2001 and Table B in the Appendix). The lack of a streamlined application process is particularly a problem in Scotland, Canada and the USA.

2. Many countries are struggling to balance the growth of viable aquaculture industries with the issues of environmental protection and social expectations for the use of water space. This is particularly an issue in New Zealand, where the limits on access to appropriate water space for aquaculture has impeded implementation of recognised best management practices and limited expansion of the aquaculture industry. There is considerable public consultation of individual aquaculture resource consents in New Zealand, which also results in lengthy (and costly) delays to the producer.

3. In Australia and Scotland the government is required to create marine development plans where aquaculture is permitted. This greatly reduces the time and cost required for new aquaculture applications (within permitted areas) because environmental impact assessments and public consultation requirements of new farms are greatly reduced.

4. Legislation in the Northern Hemisphere countries is very focused on escape prevention, protection of wild salmon stocks and fish health management, which is of less importance in New Zealand and Australia, where salmon is non-native.

5. Environmental impact in North America is primarily assessed by chemical measures e.g. free sulfides and redox potential, which have been validated as proxy measures of ecological benthic impact. The use of chemical measures provides a non-subjective assessment, reduces compliance costs and allows for greater spatial replication, which will improve far-field assessment and forecasting.

6. New Zealand is the only country that does not have legislated aquaculture monitoring requirements and regulations on permitted environmental standards. Creation of aquaculture regulations is likely to remove inconsistencies in environmental standards and enable better enforcement of environmental standards.

7. Thresholds are present in some countries/jurisdictions (Scotland, USA and Tasmania) where either EIA or consents are not required for aquaculture operations below certain production thresholds.

8. Voluntary BMP certification schemes (GAA, ASC) have higher environmental performance standards than those of national regulators.

In the following sections 2.2 to 2.9, the mandatory regulations and voluntary BMP relevant to finfish farming for Norway, Scotland, Canada, Australia, USA and New Zealand are compared, as well as the BMP prescribed by the GAA and the ASC.

2.2 FARM LOCATION

Appropriate site selection for marine finfish farms is critical to minimise environmental impact, optimize fish growth and health, and minimize production costs. For example, farm sites that have low current speeds have been shown to have higher concentrations of hydrogen sulfide under the farms, decreased fish growth and higher mortality rates (Black *et al.*, 1996). Belle & Nash (2008) recommended that appropriate net-pen sites should:

1. Not be exposed to frequent or extreme weather or sea-state conditions,
2. Be an erosional (not depositional) environment with water velocities strong enough to disperse solid wastes, but not stronger than the typical swimming speeds of the cultured species. Localised (near-field) environmental impacts caused by fish waste are much reduced in high current flow areas (Hargrave, 2003). Farms sited in more exposed areas with current velocities of >0.5 m s^{-1} are not uncommon now (Scott, 2010; Bergheim, 2012).
3. Have a water depth at least twice the depth of the net-pen to allow good water exchange and dispersal of solid wastes. Distances of <5 m between the bottom of the external net (may be a predator net) and the sea bed are considered insufficient to allow dispersal of particulate waste (Hargrave, 2002). Consequently, any site with <5 m separation between the bottom of the net-pen and the sea bed would require additional management of particulate deposition e.g. fallowing or feed and stock management.
4. Have a sea bed substrate and topography that will allow for a stable mooring.
5. Not be sited in areas frequently subjected to harmful algal blooms.
6. Not be sited in areas of high ecological significance or used by sensitive wildlife populations.
7. Not be sited in areas where there are high concentrations of predators or pests of the cultured species, or too close to other fish farms.

All six countries reviewed have a requirement for the collection of some baseline data prior to a new finfish farm licence (Table 1). In addition, an EIA is required for all new finfish licence applications in New Zealand, most applications in the USA, and for large farms in Scotland and Norway (Wilson *et al.*, 2009). EIA requirements in Canada are currently unclear because of the recent changes to the Canadian Environmental Assessment Act (2012).

Many countries also have a minimum allowable distance between farms to try and limit the cumulative environmental impact of aquaculture and the transmission of diseases and parasites between farms. A minimum of 610 m is required between finfish farms in Maine; 1 km is required between farms in Norway, Canada and Tasmania; and 8 km is required between farms in Scotland (Table 1). It should be noted that there is no evidence that separation distances of 1 km or less will prevent the transmission of diseases or parasites between farms (Stewart, 1998). Separation distances of at least 5 km have been recommended to limit disease transmission between farms (Jarp & Karlsen, 1997).

Table 1. Regulations and BMP for farm location. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Baseline data required for new farms and an expert report is required attesting that the farm can meet the required environmental standards. • Farms must not be located in areas that are 'sensitive or critical' to other species.	(GAA, 2011)
Global ASC salmon standard	• Farms must not be located in high conservation value areas.	(ASC, 2012)
Norway	• Some baseline data required prior to a new consent including average current speed, sediment characteristics, salinity and seabed topography. • New farms require an EIA if production volume is ≥36,000 m^3 for permanently sited pens, or ≥48,000 m^3 for movable pens. • Farm separation buffer ≥1 km. Farms must be ≥5 km from 'important' rivers.	(Maroni, 2000; Dow, 2004; Wilson *et al.*, 2009)
Scotland	• Baseline site information for benthic monitoring, sampling and reporting, and compliance with standards for chemical indicators in the benthic environment are required. • New farms require an EIA if they will produce >100t yr^{-1}, or are >1000 m^2 or located in a sensitive habitat. • Farm separation buffer ≥8 km[8]. • The location of net-pens should provide adequate water flow for fish, but not be so strong that fish cannot maintain their position.	(FAO, 2005a; SFAWG, 2006; Scott, 2010)
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• Baseline data required, eg., average current speed, redox, % organic matter and sulfide. Baseline data requirements for BC are more specific than for any other jurisdiction. • BC: Farm separation buffer ≥1 km from farms owned by the same company, salmon-bearing rivers and major herring spawning sites; ≥3 km from farms owned by other companies; and ≥300 m from intertidal shellfish beds. • NS: Farm separation buffer ≥1 km. • NB: Farm separation buffer ≥300 m.	(Wilson *et al.*, 2009; Cohen, 2012)
USA (Washington (WA), Maine (ME))	• Baseline site information for benthic monitoring, sampling and reporting, and compliance with standards for chemical indicators is required for all farms in ME and for farms producing >45 t per year in WA. • ME: Farm separation buffer ≥610 m. • ME: Mean current speed mid-water under the pens must be ≥5 cm s^{-1}. • ME: Farms must not be located in areas that have persistent water stratification. • ME: Horizontal predator nets must be >1 m above the sea floor.	(Aquaculture Lease Regulations, 1983 (Maine); SMDEP, 2008)
Australia (South Australia (SA), Tasmania (T))	• Regulatory authorities are required to prepare marine farming development plans for areas where marine farming is permitted. Aquaculture is not allowed outside designated aquaculture zones. • T: Regulatory authority collects baseline data on lease areas to include benthic habitat (flora, fauna and sediments) and water quality information. • Baseline site information for benthic monitoring required prior to a new site consent. • T: EIA required for new farms that produce >100 t yr^{-1}. • T: Farm separation buffer ≥1 km between farms owned by the same company and/or between different companies[8]. • SA: ≥3 m clearance is required between the bottom of the net-pen and the seabed.	(Marine Farming Planning Act, 1995 (T); Aquaculture Act, 2001 (SA); Crawford, 2003; Productivity Commission, 2004)

[8] Subject to negotiation/exception

Country	Regulations	Reference
	• T: ≥1 m clearance is required between the bottom of the net-pen and the seabed.	
New Zealand	• General requirement for baseline data and EIA for all new farms.	(Resource Management Act, 1991 (NZ); Fisheries Act, 1996 (NZ))

2.3 PRODUCTION AND STOCKING

Operational procedures such as stocking densities, net-pen designs and production cycles are generally unregulated and are left to the farm management team. The exception to this is the mandatory requirement for single-year class production in Norway, Canada and the ASC standards to help control disease and parasite transmission (see section 2.7.2), and a prescribed maximum stocking density of 25 kg m^{-3} for salmon in Norway and Tasmania.

2.3.1 Stocking densities

Typical stocking densities for marine farmed Atlantic salmon are between 7–11 kg m^{-3}, with densities reaching 18–25 kg m^{-3} just before harvest (Stewart, 1998; Hargrave, 2002; Johansson *et al.*, 2006; Belle & Nash, 2008; ACFFA, 2010). In New Zealand there is no legislated maximum stocking density. Chinook salmon are initially stocked at densities of ≤1 kg m^{-3}, with densities increasing to 20–25 kg m^{-3} just prior to harvest (New Zealand Salmon Farmers Association, 2011; M. Gillard, NZKS, pers. comm.).

There is a large variation in recommended optimal stocking densities for marine farmed Atlantic salmon from ~10 kg m^{-3} (Stewart, 1998; Laird & Kennedy, 2002) to 27 kg m^{-3} (Oppedal *et al.*, 2011b). This large variation in optimal stocking density is primarily because the effect of stocking density on the growth and performance of fish is also affected by other factors such as food availability (Robel & Fisher, 1999), water temperature and quality (Ellis *et al.*, 2002), tank cleaning disturbance (Adams *et al.*, 2007) and utilised net-pen volume (Oppedal *et al.*, 2011a; 2011b). Oppendal *et al.* (2011b) found that the maximum stocking density for optimal growth of Atlantic salmon was 27 kg m^{-3}. At densities above 27 kg m^{-3} fish showed reductions in feed intake, growth and FCR and an increased incidence of cataracts. Measurement of fish welfare (assessed by blood glucose, cortisol, fin and body condition) suggests that Atlantic salmon should be kept at a maximum density of 22 kg m^{-3} (Turnbull *et al.*, 2005).

Chinook farming in Canada is conducted in the presence of endemic pathogens, notably *Renibacterium salmoninarum*, the causative agent for Bacterial Kidney Disease (Loch *et al.*, 2012). In this situation, a maximum stocking density of 12 kg m^{-3} is recommended by D. Morrison, chief veterinarian for Marine Harvest Canada (A. Forsythe, pers. NIWA, comm.).

However, lower stocking densities may not necessarily be better than higher densities (below the optimal maximum) because of increased aggression among fish. Atlantic salmon cultured in tanks showed less aggressive behaviour and had higher welfare scores when cultured at 25 kg m^{-3} compared to fish cultured at 15 kg m^{-3} (Adams *et al.*, 2007). Similarly, Atlantic salmon cultured at 30 kg m^{-3} had faster growth rates and better body condition (but more fin damage) than fish cultured at 8 kg m^{-3} (Cañon Jones *et al.*, 2011). Producers will need to determine their own optimal stocking densities based on their site characteristics and operational practices.

2.3.2 Net-pen design

Nearly all marine farmed finfish are held in 'gravity' type net-pens that consist of a floating collar from which a net is suspended (Klebert *et al.*, 2013). Deformation of the net by water currents is minimised by weights hung from the bottom of the net or by a rigid sinker tube (Masser & Bridger, 2007). Traditionally, salmon were held in small (2000–9000 m^3), rectangular or square net-pens, that were joined together by a floating steel platform. These net-pens were relatively expensive to purchase (based on productivity), but allowed for easier handling of net changes and stock surveillance (Scott, 2010). More recently, producers have been moving towards much larger net-pens that have volumes of between 20,000–80,000 m^3 (Oppedal *et al.*, 2011a), which allow for better operational efficiencies and economies of scale (Scott, 2010; Klebert *et al.*, 2013). Square/rectangular net-pens are still used, which typically have 20–40 m long sides, depths of 20–35 m deep and are arranged in groups of 4–28 net-pens. However, circular net-pens with a high density polyethylene (HDPE) collar are becoming increasingly popular because they are cheaper than the traditional steel net-pens, and are more resilient in exposed weather/wave conditions (Masser & Bridger, 2007; Bergheim, 2012). Circular net-pens typically have a diameter of 19–64 m, a depth of ≤48 m deep and are usually moored in a gridded array with other net-pens with distances of ~20 m between net-pens (Oppedal *et al.*, 2011a). The major disadvantage of HDPE net-pens is that their working platforms are less stable than the steel platforms, and therefore, a separate working barge is required for heavy operational work (Masser & Bridger, 2007).

Net-pen design and arrangement can have large impacts on the current flow within the net-pens (Klebert *et al.*, 2013). Net-pen arrays have traditionally been orientated with their longest dimension parallel to the predominant current flow to reduce the forces on the mooring system. However, this arrangement means that the most downstream net-pen will experience reductions in water exchange, which may result in lower dissolved oxygen conditions and increased waste loads (Klebert *et al.*, 2013). For example, the downstream velocity reduction between adjacent net-pens was estimated to be between 20 and 58% depending on the solidity of the net mesh, and these reductions are cumulative when multiple net-pens are joined together (Fredriksson *et al.*, 2007). Reductions in velocity are much less in individually located net-pens, because the water velocity is only affected by one layer of net (Klebert *et al.*, 2013). In order to maximise the water flow through the net-pens, they should ideally be individually positioned with sufficiently large distances between net-pens. Rows of individual net-pens should be staggered in relation to one another, and consideration should be given to positioning arrays of net-pens so that their longest axis is perpendicular to the predominant current direction (Madin *et al.*, 2010). Recent improvements in the engineering design of mooring systems have greatly increased the hydrodynamic forces that aquaculture systems can withstand (Turner, 2000; Langan, 2012), however, the trade-off between increasing water flow and increasing drag on the mooring systems needs to be considered for each site.

Table 2. Regulations and BMP for production and stocking. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Records of annual production must be kept. • Farms shall co-ordinate production, stocking and fallowing cycles with neighbouring (≤ 5 km radius) Best Aquaculture Practices (BAP) certified farms, or farms belonging to the same AMA. • Stocking densities should be ≤25 kg m^{-3}.	(GAA, 2011)
Global ASC salmon standard	• All fish on site must be of a single-year class (≤6 mths between smolt inputs is permitted as long as the site is fully fallowed after harvest).	(ASC, 2012)
Norway	• Records of stocking density and biomass must be kept, maximum stocking density is 25 kg m^{-3}. • Maximum allowable biomass and maximum annual production is stipulated in licence conditions (900 t for Troms and Finnmark and 780 t for the rest of Norway). • Only single-year class production is allowed.	(Maroni, 2000; Wilson *et al.*, 2009; Bergheim, 2012; Marine Harvest, 2012)
Scotland	• Fish health and dissolved oxygen (DO) levels should be monitored regularly to prevent over-crowding. Corrective action should be taken if DO levels fall below the critical level for the species.	(SFAWG, 2006)
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• BC: Records of stocking density, monthly peak biomass, and year-class composition must be kept. Maximum allowable biomass is stipulated in licence conditions. • Only single-year class production is allowed.	(Brooks *et al.*, 2002; Cohen, 2012; Marine Harvest, 2012)
USA (Washington (WA), Maine (ME))	• Records of production and stocking densities must be kept. • ME: Maximum stocking density is stipulated in lease conditions.	(SMDEP, 2008; Wilson *et al.*, 2009)
Australia (South Australia (SA), Tasmania (T))	• SA: Records of stock must be kept including number of fish and monthly biomass. • T: Maximum stocking density is 25 kg m^{-3}.	(Aquaculture Act, 2001 (SA); Crawford, 2003; FAO, 2010)
New Zealand	• Records of annual production and stocking densities must be kept. • Net-pen design and location is specified in some resource consents. Generally, there is very limited room to move net-pens within the licensed area.	(Fisheries Act, 1996 (NZ); Wilson *et al.*, 2009; M. Gillard, NZKS, pers. comm.)

2.4 FEED MANAGEMENT

The cost of feed is, on average, between 40–50% of total production costs (Marine Harvest, 2012), and therefore, optimising feed management is critical to the economic performance of fish farms. The feed type needs to be carefully formulated to optimise nutrient retention and FCR in fish, particularly by maximising digestibility, and protein and phosphorus retention. Commercially competitive FCR for farmed Atlantic salmon are now reported to be around 1.0–1.15 (Sveinson & Engelstand, 2001; Storebakken, 2002; Belle & Nash, 2008; Bureau & Hua, 2010). However, there is some uncertainty in comparing reported feed efficiency measures because the methodologies used to calculate measures such as FCR are rarely clearly stated. For example, the FCR is dependent on whether: 1) it is calculated on an "as-fed" or dry weight basis; 2) the quantity of feed is calculated as total feed purchased, feed offered or feed consumed; 3) the quantity of fish produced includes losses (mortalities and escapes); and 4) the quantity of fish produced is calculated on a live weight or post-harvest (bled) weight. A meta-analysis of aquaculture feed efficiencies report an average FCR for salmon (Atlantic, Coho and Chinook) of 1.25, with a range of 1–1.6 (Tacon & Metian, 2008).

High-quality fish feeds can now contain very high lipid concentrations (>30%), which enhances fish growth and spares dietary protein for tissue synthesis rather than energy production (Amirkolaie, 2011). In salmonids, a digestible protein: digestible energy concentration of 18 g protein MJ^{-1} reduces protein catabolism without adversely affecting growth or feed efficiency (Einen & Roem, 1997). Use of highly digestible, high-lipid feeds have increased the protein retention of cultured fish from 20–25% to ≤40%, and decreased the production of solid nitrogenous waste by more than 25% (Belle & Nash, 2008; Bureau & Hua, 2010).

Feeding frequency, pellet size and feed quantity are other critical parameters. Under-feeding of fish results in slower growth rates, increased aggression, and a large range in fish size within a cohort, while over-feeding of fish results in unnecessarily high feed costs, poor FCR and increased pollution (Storebakken, 2002). In well-managed farms, feed losses of uneaten food are less than 1% (A. Forsythe, NIWA, pers. comm.). The optimal feeding frequency and quantity depends on fish size and water temperature. Fish cultured in sea-pens are often fed every 0.5–2 h during daylight, however, maximum growth can be achieved by feeding only 3–4 times per day (Storebakken, 2002). It is important that sufficient food is given per feeding occasion, and that the food is spread over a wide area, to prevent dominant individuals from monopolising the food (Storebakken, 2002). Pellets should not be dispensed too close to the edges of the nets or when tidal currents are very strong, because they will be swept out of the pens before they can be consumed. Pellet size also affects FCR and wastage; small pellets require more energy expenditure per kJ consumed and also produce more wastage (Belle & Nash, 2008). In general, pellet diameter should be around 2.5% of the fork length (FL) of the fish for salmon (Wànkowski, 1979).

An essential component of optimal feed management is accurate and regular monitoring of feed consumption rates, fish size and biomass, so that feeding frequency and quantity can be accurately tailored to the fish stock (Belle & Nash, 2008). For example, as a precautionary approach salmon farmers on the Canadian Atlantic coast stop feeding fish when the dissolved oxygen concentration falls below 6 mg l^{-1} (Burt *et al.*, 2012), because fish have a reduced appetite at these dissolved oxygen concentrations (see Section 2.7.1 for more information). All six countries require records of production, stocking biomass and feed input to be kept, providing a long-term record that can be used for feed management. In some jurisdictions, the requirement to minimise feed loss is legislated through measures such as mandatory real-time feed monitoring (Maine) and the prohibition of feeding during times of strong currents (New Brunswick and Nova Scotia) (Table 3). In New Zealand, environmental impact of finfish farms is managed through a maximum feed quota that is set for each site, rather than a maximum production biomass.

Table 3. Regulations and BMP for feed management. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Records of feed input must be kept, including C and N content of feed. • The fish in: fish out (FIFO) ratio[9] must be ≤ 2. After 2016 the FIFO ratio must be ≤1.5. • Fish feed shall be made by a reputable company.	(GAA, 2011)
Global ASC salmon standard	• Fines (particles <1 mm in diameter) in feed with a diameter of 5 mm must be <1% by weight. • Fishmeal feed fish dependency ratio (FMDR) must be <1.35 and the fish oil feed fish dependency ratio (FODR) must be <2.95[10].	(ASC, 2012)
Norway	• Records of feed consumption must be kept (maximum feed quota has been removed). • Feed loss should be reduced as much as possible.	(Maroni, 2000; Wilson *et al.*, 2009; Bergheim, 2012)
Scotland	• Records of feed consumption must be kept. • Farmers should ensure that feed composition, pellet size and quantity are optimal for the species and stage. • Wet feeds used for broodstock should be treated to minimise risk of microbial contamination.	(SFAWG, 2006)
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• Records of feed consumption must be kept including quantities of feed pigments used. • NB, NS: Feeding must be monitoring regularly and stopped or reduced if feed consumption rates decrease. • NB, NS: Feeding must not occur during times of high current velocities. • NB, NS: All possible measures must be taken to minimise feed loss.	(Government of New Brunswick, 2006; Cohen, 2012)
USA (Washington (WA), Maine (ME))	• Records of feed consumption must be kept. • ME: Real-time monitoring of feed consumption required. Feed loss must be minimised. • WA: Feed loss will be minimised. Feeding methods will be used to ensure all fish receive adequate food.	(Washington Fish Growers Association, 2002; SMDEP, 2008; Wilson *et al.*, 2009)
Australia (South Australia (SA))	• SA: Records of feed consumption must be kept. • SA: Feed used must not increase the transmission risk of notifiable diseases.	(Aquaculture Act, 2001 (SA); FAO, 2010)
New Zealand	• Records of feed consumption must be kept. • A maximum annual feed input is set for each farm. • Records of feed compositions must be kept. • Feeds shall be formulated for the species, life-stage, environment and feeding system used. • Feed management plans and on-going assessment of feed management are required to minimise wastage and adverse environmental impacts. • Feed storage and delivery systems shall be secure and properly	(NZ Salmon Farmers Association Inc, 2009; Wilson *et al.*, 2009)

[9] FIFO = feed fish inclusion factor × FCR
Where Feed fish inclusion factor = (% fishmeal in diet + % fish oil in diet) / (yield of fishmeal +yield of fish oil)
If no yield information is available, the fishmeal yield is assumed to be 22.5% and the fish oil yield is assumed to be 5%.
[10] FMDR = (% fishmeal in feed fish × FCR)/24
FODR = (% fish oil in feed fish × FCR)/5 or 7 (see ASC, 2012 for further details)

Country	Regulations	Reference
	maintained to prevent spoilage, catastrophic loss and consumption by wildlife.	

2.5 ENVIRONMENTAL EFFECTS AND WASTE MANAGEMENT

Organic enrichment of the environment around net-pens leading to a change in benthic macrofauna and sediment characteristics, and sometimes, the development of anoxic conditions, is arguable the major adverse environmental impact of fish farming (Brooks *et al.*, 2002). In heavily enriched conditions, microbial degradation of organic matter consumes all the available dissolved oxygen, resulting in anoxic conditions in the sediment and the production of hydrogen sulfide gas (Backman *et al.*, 2009). Concentrations of hydrogen sulfide in the bottom water below net-pens have been shown to be negatively correlated to the fish growth (r = -0.82) and positively correlated to cumulative mortality in salmon (r = 0.94), with detectable impacts at mean concentrations as low as 2.5 µM (Black *et al.*, 1996). It has been proposed that hydrogen sulfide toxicity may not be directly responsible for the poor performance of fish, but may only be symptomatic of sub-optimal culture conditions, because hydrogen sulfide is rapidly diffused in the marine environment and it is very unlikely that fish held in surface net-pens will be exposed to toxic concentrations of hydrogen sulfide[11] (Black *et al.*, 1996; Brooks *et al.*, 2002). Anoxic conditions and hydrogen sulfide production are most commonly associated with intensively-used shallow sites that have low current velocities.

2.5.1 Environmental monitoring for impact management

Regular environmental monitoring is essential for managing fish health, production and environmental impact. Frequent monitoring of dissolved oxygen, water temperature and salinity are necessary to ensure optimal fish health and production (see Section 2.7.1 for more information). Regular monitoring of the sediment and benthos underneath the farms is required to assess the environmental impacts of the farm. All six countries reviewed (with the exception of New Brunswick and Nova Scotia) have fairly comprehensive near-field environmental monitoring requirements, which typically include video or diver surveys, benthic macrofauna assessments, and quantification of various chemical parameters in the water and sediment (Table 4). Environmental assessments in New Brunswick and Nova Scotia are primarily based on free-sulfide measurements under the farms (Wilson *et al.*, 2009). Environmental monitoring requirements in Norway, Nova Scotia and New Brunswick are based on a feedback system where lower impact sites have less monitoring requirements than higher impact sites. Similarly, in Scotland and Washington, the environmental monitoring requirements increase with increasing production volume. If environmental thresholds are exceeded then control measures such as a reduction in production levels, reduction in feed input or a mandatory fallowing period are likely to be instigated.

In areas where there are numerous marine farms there is the potential for a cumulative impact on the environment. To ensure that the carrying capacity of the environment is not exceeded, the environmental impacts of aquaculture cannot be considered on a farm-by-farm basis, but must be considered on a wider, regional scale. Potential far-field impacts of aquaculture include eutrophication of the water column, an increase in harmful algal blooms, widespread modification of the benthic environment, genetic modification of wild fish stocks, disease transmission to wild fish and transmission of biosecurity pest species (Gibbs, 2012). Current environmental monitoring requirements focus heavily on the near-field (<50 m from net-pens) impacts of individual farms, which does not provide the necessary information required by

[11] Hydrogen sulfide was only detected in the water just above the sediment at slack tide. It was never detected at the level of the net-pens.

regulators in order to allow for expansion of the aquaculture industry while minimizing its environmental impacts (King & Pushchak, 2008; Gibbs, 2012). However, attempts to directly quantify far-field impacts of finfish farms that are sited in open-water, marine environments have generally failed to detect a significant impact on dissolved nutrients or phytoplankton growth (e.g. Merceron *et al.*, 2002; Alongi *et al.*, 2003; Soto & Norambuena, 2004; Pitta *et al.*, 2005). Significant impacts of finfish farms on water parameters have typically only been detected in farms located in semi-enclosed bays with restricted water flow or in areas that contain a very large number of fish farms (Tovar *et al.*, 2000; Nordvarg & Johansson, 2002).

It has been suggested that marine finfish farming has increased the incidence of harmful algal blooms through increased dissolved nutrients in the water. Certain harmful algae species such as *Gymnodimium mikimotoi* and *Phaeocystis pouchetii* are associated with eutrophic waters and substantial blooms of these species appear to be stimulated by nutrient enrichment and an increase in the ratio of nitrogen and phosphorus to silicon (Scottish Association for Marine Science & Napier University, 2002). However, there is no conclusive evidence that increased nutrient inputs from finfish farms cause an increase in the frequency of harmful algae blooms, except in a few small, enclosed waters (Scottish Association for Marine Science & Napier University, 2002; Tett & Edwards, 2002; Hargrave, 2003).

Similarly, far-field changes to the benthic macrofauna community or sediment composition are infrequently detected, with most changes limited to an area within 50 m of the net-pens (e.g. Iwama, 1991; Ye *et al.*, 1991; Findlay *et al.*, 1995; Black, 2001; Hargrave, 2003; Sutherland *et al.*, 2007). The general lack of detection of significant far-field impacts does not necessarily mean that they do not occur, but may be because current monitoring methods lack the resolution to detect far-field impacts. A few studies have shown that finfish farming can cause far-field effects on the sediment and macrofauna community, particularly in high-current environments. Hall-Spencer *et al.*, (2006) found that live maerl cover (red coralline algae) was significantly lower within 100 m of a fish farm than at reference sites. Wong *et al.* (1999) found evidence that intertidal infauna diversity was significantly lower at sites <500 m from salmon farms, though species abundance was not affected by proximity to the farms.

More recently, research has moved away from trying to directly measure the far-field impact of fish farms to the development of 3D biogeochemical models that estimate the nutrient and plankton concentrations in a region based on nutrient inputs from multiple local sources (e.g. fish farms, land run-off, natural marine sources) (Henderson *et al.*, 2001). Predictions from some of these 3D models show good correlations with observed data (e.g. Sutherland *et al.*, 2009; Wild-Allen *et al.*, 2010; Tsagaraki *et al.*, 2011), and are likely to be a useful tool for estimating the carrying capacity of a particular environment and how many finfish farms an environment can sustainably support. Collection of long-term environmental data coupled with the development of biogeochemical models will allow region-specific environmental management plans to be developed, and future research should focus on the development of better models for the major aquaculture regions. Models are currently used for aquaculture management in parts of Tasmania, Scotland, Norway and Canada (CSIRO Huon Estuary Study Team, 2000; Cromey *et al.*, 2002; Wilson *et al.*, 2009).

2.5.2 Fallowing

Fallowing of impacted sites is the most commonly utilised method of site remediation. Research has shown that chemical remediation (the return of sediment chemistry to reference levels) of moderately impacted sites can be achieved in 4–6 months (Brooks *et al.*, 2003), and biological remediation (development of a benthic macrofauna community similar to those at reference sites) can be achieved in 3–36 months (Ritz *et al.*, 1989; Karakassis *et al.*, 1999; Brooks *et al.*, 2003; Macleod *et al.*, 2004). However, remediation times are highly site-specific and it can take 2–5.5 years to achieve chemical remediation in some heavily impacted sites (Brooks *et al.*, 2004; Macleod *et al.*, 2004) and up to 10 years to achieve biological remediation (Dunmore *et al.*, 2013b). Remediation time depends on numerous factors including the depth of organic matter accumulation, water depth, current velocity, site production history, and the physical and chemical characteristics of sediment and water (Belle & Nash, 2008; Backman *et al.*, 2009). At most sites, chemical remediation can be achieved after 4–6 months of fallowing, and biological remediation after 1 year (Brooks *et al.*, 2003; Belle & Nash, 2008). Producers who use fallowing as a means of site remediation typically practice site rotation between 2 or 3 sites. That way, sites can be left to fallow for relatively long periods of time (3–24 months) without affecting production levels (Scottish Executive, 2000). In on-going farming operations it is not necessary for the site to achieve complete remediation, but only recovery to a level that will allow it to withstand further organic enrichment without suffering any cumulative deterioration (Macleod *et al.*, 2007). A three month fallowing period was found to be adequate to return the macrobenthic community structure under two salmon farms to their pre-stocking structure, but not to reference levels (Macleod *et al.*, 2006), though the required fallow period is likely to vary greatly among sites.

Only South Australia and Norway (and the ASC standard) have mandatory fallowing periods after every production cycle, which are also used to manage disease transmission (see Section 2.7.2 for further information). Farms in British Columbia, Tasmania and Washington are required to have a fallow period if they do not meet certain environmental criteria, and restocking of net-pens is not permitted until measured environmental parameters are below threshold criteria (Table 4). Many producers now voluntarily use routine fallow periods to help minimise organic enrichment under the net-pens and for disease control (Crawford, 2003; Backman *et al.*, 2009; Walker *et al.*, 2012). For example, in Scotland fallowing is not mandatory but in 2011, 76% of active sites were fallowed for between 4 and 52 weeks, with 15% of sites fallowed for at least 52 weeks (Walker *et al.*, 2012).

Uptake of fallowing for site remediation by all producers is hindered by the lack of sufficient rotation sites (Stewart, 1998). If farming operations cannot be shifted to a secondary site during the fallowing period, then overall production is severely curtailed. For fallowing to be successfully implemented as a method of minimizing environmental impact, farms require double their current water space, so that they are able to maintain their production levels while leaving other sites to fallow (Scottish Executive, 2000).

2.5.3 Integrated aquaculture

Integrated aquaculture (polyculture) of finfish with shellfish, seaweeds, sea urchins or sea cucumbers has been researched in several regions as a method of mitigation for finfish farms. It has been proposed that seaweeds cultured near finfish farms can be used to reduce the inorganic nutrient load on the environment produced by finfish farms, and shellfish, sea urchins and sea cucumbers can be used to reduce the organic nutrient load on the environment (McVey *et al.*, 2002). In addition, integrated aquaculture may produce a secondary source of income, depending on the species cultured. Unfortunately, the value of integrated nutrient and energy exchange for the production of commercial products across the trophic chain has not been realised in either ecological or economic terms.

The integrated aquaculture of fish with plants has been practiced on land for centuries (Neori *et al.*, 2004). More recently, integrated culture of fish and seaweed has been proposed as a method of mitigating the environmental impacts of marine aquaculture (Kautsky & Folke, 1991; Neori *et al.*, 2004). Early enthusiasm for integration of production systems was supported by studies which showed that the growth of seaweed cultured near finfish farms is significantly greater than the growth of seaweed at control sites (Ruokolahti, 1988; Rönnberg *et al.*, 1992; Troell *et al.*, 1997; Chopin *et al.*, 1999). Seaweeds have been estimated to be able to remove a significant proportion of the ammonia, nitrogen and phosphorous produced by finfish farms (Troell *et al.*, 1997; Troell *et al.*, 1999). For example, 10 t of macroalgae grown near a finfish farm that produced 230 t of fish per annum was estimated to remove 27% of the dissolved phosphorus and 5% of the inorganic nitrogen produced by the fish farm (Troell *et al.*, 1997). However, in the absence of evidence that these activities diminished undesirable environmental effects of the farm and improved core business performance (through mechanisms such as improved fish health or farm capacity) or represented a competitive business investment in its own right, the value of these activities is limited to brand development.

Deposit-feeding sea urchins and sea cucumbers cultured directly under finfish farms have the potential to reduce the quantity of organic matter settling on the seabed. Studies have shown that sea urchins and sea cucumbers had a high assimilation efficiency of fish feed and faeces (Nelson *et al.*, 2012), grew significantly faster under fish farms than at control sites (Ahlgren, 1998; Kelly *et al.*, 1998; Cook & Kelly, 2007; Yokoyama, 2013), and showed high survival rates (Kelly *et al.*, 1998; Yokoyama, 2013). In the New Zealand context, the use of deposit-feeding echinoderms for assimilation of organic matter produced by finfish farms appear to be limited (A. Forsythe, NIWA, pers. comm.).

Results on the use of filter-feeding shellfish to reduce the organic nutrient load produced by finfish farms are more equivocal. A number of studies have shown that shellfish cultured near finfish farms grew significantly faster than shellfish at control sites (Jones & Iwama, 1991; Lander *et al.*, 2012; Jiang *et al.*, 2013), presumably because they were feeding on the organic matter produced by the fish farm. Mazzola & Sarà (2001) used stable isotope ratios to estimate that mussels suspended adjacent to a finfish farm located in sheltered waters (<10 cm s^{-1}) may derived around 50% of their diet from uneaten fish food and faeces, and clams that were placed directly below the finfish farm may derive around 80% of their diet from uneaten fish food and faeces. However, other studies have shown that integrated aquaculture of fish and shellfish has no effect on the growth of shellfish and there was little evidence that shellfish were feeding on fish feed or faeces (Cheshuk *et al.*, 2003; Navarrete-Mier *et al.*, 2010). It should be noted that the possible benefits of integrated culture of shellfish and finfish are strongly dependent on the location of the marine farm and the proximity of the mussels and fish. Generally, farms need to be located in regions with low current speeds (<10 cm s^{-1}, which are not ideal for finfish farms) and low ambient seston concentrations (<5 mg l^{-1}) for a detectable reduction in dissolved organic matter to be observed (Troell & Norberg, 1998), and mussels and fish must be cultured in close proximity. Mussels cultured within 10 m of fish farms typically show greater growth than mussels at control sites (Cook *et al.*, 2003; Robinson *et al.*, 2003; Lander *et al.*, 2012), while mussels cultivated at distances greater than 10 m often show similar growth rates to mussels at control sites (Cheshuk *et al.*, 2003). These results are in agreement with Lander *et al.* (2012) who found that the concentration of fine suspended particles decreased substantially at distances of more than 10 m downstream from the fish net-pens.

Integrated aquaculture activities in the regions under consideration in this document remain at a research scale. Integrated aquaculture of salmon and seaweed is currently being trialled in Scotland (SAMS, 2012), and integrated culture of fish, seaweed and shellfish is being trialled in Canada and the USA (Belle & Nash, 2008; Canadian Aquaculture, 2012). A very significant public investment into integrated aquaculture in Canada has failed to attract substantive commercial interest (F. H. Page, per. comm.).

Table 4. Regulations and BMP for waste management. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Existing farms are required to provide three years of monitoring data to show that they meet the environmental standards. • Environmental monitoring of sediment is required, monitoring is to coincide with annual peak feeding time. • Adherence to the Allowable Impact Zone (AIZ) defined in country regulations is required. If not AIZ is defined by the country then the AIZ is set at a 40 m radius around the farm boundary. Outside this zone there must be no statistically significant accumulation of sediment. • All possible measures shall be taken to prevent pollutants from being discharged into the sea. • Garbage and solid wastes shall be disposed of appropriately on land.	(GAA, 2011)
Global ASC salmon standard	• AIZ is a 30 m radius around the farm. Outside this zone the redox potential must be >0 mV or sulfide must be ≤1,500 µM l^{-1}. • Faunal indices show good to high ecological quality outside the AIZ (e.g. Shannon-Wiener Index >3). • Within the AIZ ≥2 species, which are not pollution indicator species, must be present in high abundance (= reference site densities or >100 ind.m^{-2}). • Average weekly DO must be ≥70% saturation. More than 95% of readings must be >2 mg l^{-1}. • Farms must monitor N and P concentrations in the water weekly. • Garbage and solid wastes shall be disposed of appropriately on land.	(ASC, 2012)
Norway	• Environmental monitoring required including organic sediment loading, benthic macrofauna, pH, redox, total organic content and grain size of the sediment and DO of water. • Monitoring requirements are dependent on the level of impact under the farms. • Mandatory fallowing in line with regulations at the time. The fallowing period is typically around 6 months. Licence may be withdrawn if the site is still highly impacted after fallowing.	(Maroni, 2000; Dow, 2004; FAO, 2005b; Wilson *et al.*, 2009)
Scotland	• Environmental monitoring required including video surveys, NH_3, NH_4, DO, P, Chl *a* and Cu in the water, and benthic macrofauna, redox, total organic carbon, grain size, Cu, Zn, free sulfide and specific therapeutants in the sediment. Presence of *Beggiatoa* sp. and feed pellets under farms is also monitored. • DO must be ≥7 mg l^{-1}, • Cu must be ≤270 mg kg^{-1} (DW) inside AIZ (~25 m)[12] and ≤34 mg kg^{-1} outside AIZ. • Zn must be ≤410 mg kg^{-1} inside AIZ and ≤150 mg kg^{-1} outside AIZ • S must be ≤4800 µM inside AIZ and ≤3200 µM outside AIZ. • No feed pellets or *Beggiatoa* sp. permitted outside AIZ. • Number of taxa outside AIZ must be ≥50% of reference levels. Must have at least 2 polychaete species inside AIZ. • All wastes must be disposed of according to legislation, dead fish and waste must not be used as bait. • Blood water and effluent should be contained and disposed of appropriately. • Transport water should not be disposed of in natural waterways.	(Thomson & Side, 2002; SFAWG, 2006; Wilson *et al.*, 2009)
Canada (British Columbia	• Baseline environmental monitoring required including benthic macrofauna, pH, redox, total organic content, grain size, free sulfide, Cu and Zn concentrations in	(Brooks *et al.*, 2002;

[12] AIZ distance in new consents is calculated by models and varies among farms.

Country	Regulations	Reference
(BC), Nova Scotia (NS), and New Brunswick (NB))	the sediment, and the presence of *Beggiatoa* sp. and feed pellets under the farms. • BC: Annual monitoring must be conducted within 30 days of peak biomass. • Free sulfide must be <6000 µM 30 m from pens. • BC: Farms cannot be restocked until free sulfide is <1300 µM 30 m from pens. • BC: Macrobenthos abundance and richness 30 m from pens must not be significantly different from reference stations. • No significant adverse impacts are allowed >100 m from net-pens. • Disposal of all wastes resulting from aquaculture operations, including domestic wastes from accommodation facilities and fish mortalities are regulated. • BC: Producers must implement a BMP that aims to minimise waste generated. • NS, NB: Oxic sites should not wash nets on site. • NS, NB: Anoxic or hypoxic sites must not wash nets on site.	Environmental Management Act, 2003 (BC); Dow, 2004; Government of New Brunswick, 2006; Backman *et al.*, 2009; Wilson *et al.*, 2009; Nova Scotia Fisheries and Aquaculture, 2011)
USA (Washington (WA), Maine (ME))	• ME: Environmental monitoring required including video surveys, pH, redox, free sulfide, benthic macrofauna, grain size, total organic carbon, Cu, Zn and therapeutants in sediment, presence of anoxic sediment or *Beggiatoa* sp. under farms, and DO, NH_3, NH_4, Chl *a*, P and Cu in water. Authorities must be notified immediately if warning levels or impact thresholds are exceeded. • WA: Biennial benthic environmental monitoring required for farms producing >45 t per year, only diver surveys required for farms producing 9–45 t per year. No monitoring of water column required. • WA: No significant negative effects allowed outside the AIZ (33 m radius from the net-pens). • Sulfides must be <6000 µM within AIZ. • WA: Failure to meet environmental criteria may result in reduction of production biomass, reduction in total feed allowed or mandatory fallowing. • ME: Domestic waste must be disposed of properly on land. No discharge of blood, viscera or transport water in the sea. • ME: DO within AIZ must be ≥6 mg l^{-1} • ME: No detectable toxins from farm allowed in sediment >30 m distance from pens. • ME: nets may only be cleaned on site if there is no accumulation of solid waste from the nets below the farm or degradation of water quality.	(Aquaculture Lease Regulations, 1983 (Maine); Brooks *et al.*, 2002; SMDEP, 2008; Wilson *et al.*, 2009)
Australia (South Australia (SA), Tasmania (T))	• SA, T: Environmental monitoring required, including video surveys and semi-quantitative macrofauna assessment. Some farms are required to collect water quality samples (N and P), benthic samples and macrofauna counts. Compliance with chemical indicator standards is required. • SA: A minimum fallowing time of 12 months is required between production cycles at the same site. • T: No visible or measurable impact allowed beyond 35 m of farm lease boundaries, including the presence of fish feed. • T: Must be no evidence of bacterial mats prior to restocking. • T: Spontaneous outgassing of the sediments requires immediate fallowing. • T: DO 5 m below surface within lease areas must always be >80% saturation or >6 mg l^{-1}, whichever is the lowest. • T: Requirement to adopt best practice with respect to treatment and disposal of greywater. • SA, T: Bloodwater and blackwater must be disposed of on land into an appropriate facility. • T: Must comply with licence conditions relating to environmental management of sewage treatment plants within marine farming lease areas. • T: Sites are typically fallowed for 3–6 months after each production cycle.	(Aquaculture Act, 2001 (SA); Productivity Commission, 2004; Woods *et al.*, 2004; FAO, 2010)

Country	Regulations	Reference
New Zealand	• Site specific environmental monitoring required based on the regional resource consent conditions and ANZECC guidelines. • Anoxic/azoic conditions not permitted (Enrichment Stage (ES) 7). • Discharge of waste and pollutants into the sea is prohibited. • Blood, harvest effluent and sewage shall be contained, collected and disposed of in an appropriate manner. • All waste material must be collected and stored in leak proof, vermin proof containers and disposed of appropriately on land.	(Aquaculture Reform Act Aquaculture Reform Act, 2004 (NZ); NZ Salmon Farmers Association Inc, 2009; Wilson *et al.*, 2009; Keeley, 2012)

2.6 USE OF CHEMICALS AND THERAPEUTANTS

Chemicals in finfish aquaculture are primarily used to disinfect equipment, prevent bio-fouling of nets and for the treatment of infected fish. There is a paucity of information on the bioaccumulation and effects of chemicals and therapeutants added to the marine environment, and there is concern that they may have a long-lasting, negative impact on the environment. The situation is complicated in that aquaculture is only one of several anthropogenic sources of metals and chemical compounds. All six countries reviewed have regulations on the chemicals that can be discharged into the marine environment and the types of therapeutants that can be used to treat fish (Table 5). To date, there has been little need for disinfectants or therapeutants in salmon farming in New Zealand (Forrest *et al.*, 2007) and the use of copper-based anti-fouling paints has been discontinued in many salmon farms (Preece, 2012b).

2.6.1 Bio-fouling management

Bio-fouling of nets and cages is a major problem for the aquaculture industry and is estimated to account for 5–10% of overall production costs (Lane & Willemsen, 2004). Colonisation of the nets by unwanted organisms has a number of negative effects including: 1) increasing net weight by more than 10 fold, which puts additional strain on mooring systems, causes net-pen deformation and increases the probability of tears; 2) decreasing the water flow through the nets, which restricts the supply of oxygen and removal of waste products from the enclosures; and 3) acting as a reservoir of harmful organisms, pest species or disease vectors (Braithwaite & McEvoy, 2005; Fitridge *et al.*, 2012). Bio-fouling can reduce the open area of net-mesh by 37% within a week (Hodson *et al.*, 1995) and water flow through the nets can be decreased by more than 50% (Gormican, 1989; Fredriksson *et al.*, 2007). Reductions in water flow are even greater when groups of net-pens are aligned parallel to the current direction, because the water is restricted by multiple layers of net and attached bio-fouling organisms (Fredriksson *et al.*, 2007; Klebert *et al.*, 2013). The combination of low water flow, net blockages and high stocking densities will reduce the dissolved oxygen within the net-pens rapidly (Johansson *et al.*, 2006) and mass mortalities of fish from anoxia have been recorded in heavily fouled nets (Braithwaite & McEvoy, 2005; Fitridge *et al.*, 2012).

Copper-based anti-foulants with/without added biocides and zinc are the only consistently effective anti-foulants currently available for commercial-scale aquaculture, and internationally the vast majority of finfish farms use copper-based anti-foulants on their nets to prevent bio-fouling (Braithwaite & McEvoy, 2005; Fitridge *et al.*, 2012). Copper and zinc from anti-fouling paints gradually leaches out of the paint, accumulating in the sediment underneath the farms. Locally elevated concentrations of copper and zinc are common directly under the net-pens (Braithwaite & McEvoy, 2005) and copper concentrations of between 50 and 150 mg kg^{-1} are typical under Canadian salmon farms (Burridge *et al.*, 1999; Chou *et al.*, 2002; Brooks & Mahnken, 2003), though concentrations of 800–1300 mg kg^{-1}

have been recorded under finfish farms (Macleod & Eriksen, 2009). These high metal concentrations may reflect historic management practices including poorly formulated anti-fouling binding agents and *in situ* cleaning of treated nets. The 'probable effects' Interim Sediment Quality Guidelines (ISQG) range for copper is 65–270 mg kg^{-1}, above which, adverse effects are likely (ANZECC, 2000). However, the negative impacts of elevated metal concentrations in the sediment below finfish farms are not well understood because of limited bioavailability. It is likely that the majority of copper and zinc in the sediment under farms will bind with sulfides and organic matter, reducing their dispersion and bioavailability (and hence their subsequent toxicity) (Brooks *et al.*, 2003; Burridge *et al.*, 2010). Furthermore, 45–92% of the copper underneath finfish farms was found to be in the form of large paint flakes (>63 µm), which have much lower bioavailability than the <63 µm fraction (Macleod & Eriksen, 2009; O'Brien *et al.*, 2009). Thus, although concentrations of metals underneath finfish farms are sometimes highly elevated, they may have a very low bioavailable percentage. It should be noted that disturbance and remediation of the sediment may re-suspend and disperse the metals, making them available for uptake (Scottish Association for Marine Science & Napier University, 2002; Macleod & Eriksen, 2009). High concentrations of metals in the sediment may also reduce the recolonisation rate of benthic fauna once the farm site has been left to fallow (Morrisey *et al.*, 2000).

Some aquaculture companies have opted to cease using anti-fouling treatments on nets to reduce the quantity of copper and zinc introduced into the marine environment. Instead, nets are cleaned by high-pressure water, either *in situ* or on land. Removal of bio-fouling from untreated nets represents a major cost for the aquaculture industry, with net changes required every 5–14 days during summer in tropical and temperate regions (Lee *et al.*, 1985; Hodson & Burke, 1994). Moreover, frequent net changes stress the fish and may result in increased fin or body damage or loss of appetite (Fitridge *et al.*, 2012). Nets are either removed and cleaned on land by high pressure water hoses or washing machines, or cleaned *in situ* by mechanical robotic cleaners or divers (Fitridge *et al.*, 2012). *In situ* cleaning may cause reductions in the water quality because of the high discharge rates of organic matter. In areas where bio-fouling rates are high and water currents are low, treatment with copper anti-fouling paints may represent a lower overall environmental risk than frequent net washing (Belle & Nash, 2008), and is likely to be better for fish welfare and growth. Accordingly, *in situ* cleaning of nets has been prohibited in New Brunswick and Nova Scotia at moderately and heavily impacted farm sites since the 1990s (Hargrave, 2003; Government of New Brunswick, 2006). However, net management protocols are rapidly evolving in response to the development of net cleaning robots and the introduction of new materials for net construction. These innovations are anticipated to have the capability to significantly reduce the adverse effects of *in situ* cleaning in future and these changes should be considered in any regulatory planning activities.

The co-culture of herbivorous fish has been proposed as a method of controlling bio-fouling (Kvenseth, 1996). In Norway, wrasse (Family: Labridae) are co-cultured with salmon to control sea lice at ratios of 1:100 wrasse: salmon, with around 60% of salmon farms now using wrasse (Holm *et al.*, 2003; Bergheim, 2012). An additional benefit of wrasse co-culture is that they also graze on bio-fouling organisms. The use of wrasse on 4 salmon farms in Norway was estimated to reduce the cost of bio-fouling management by ~NZ$20,300 (NOK $97,000) per annum (Kvenseth & Andreassen, 2003). The use of herbivorous fish for bio-fouling management is not a complete control method but will only reduce the frequency of net cleaning, because fish will only selectively consume the edible fouling species (Fitridge *et al.*, 2012).

Novel bio-fouling technologies are currently under development such as non-toxic, low surface energy polymers (Townsin & Anderson, 2009), air curtains (Scardino *et al.*, 2009) and hydrophobic compounds (Callow & Callow, 2009), however, the commercial development of these technologies still requires further research (Fitridge *et al.*, 2012).

2.6.2 Therapeutants

Disinfectants and medicines administered to farmed fish via bath treatments or orally may result in negative effects on other marine organisms, and therapeutants use is highly regulated in all six countries reviewed (Table 5). The introduction of salmonids into New Zealand occurred without the importation of their major pathogens. To date, there has been little need for therapeutants in salmon farming in New Zealand and they are not currently used in salmon farming in New Zealand (Forrest *et al.*, 2007; M. Gillard, NZKS, pers. comm.). Internationally, frequent applications of therapeutants are required in some countries to control sea lice and disease outbreaks, and there is concern that frequent use of therapeutants may have negative effects on the marine environment or lead to antibiotic-resistant strains of bacteria (Burridge *et al.*, 2010). Toxicity tests with permitted therapeutants show minimal impacts on non-target organisms when the therapeutants are used as prescribed (Burridge *et al.*, 2010). However, very little is known about the bioaccumulation and cumulative effects of therapeutants added to the marine environment (LaPatra & MacMillan, 2009).

Development of vaccines for some of the major bacterial diseases in salmon has greatly reduced the use of antibiotics. In Norway, all fish are vaccinated against at least three major bacterial diseases (vibriosis, cold-water vibriosis and furunculosis) prior to stocking in sea-pens. This has resulted in a dramatic decrease of >99.9% in the amount of antibiotics used per unit biomass produced since the 1980s (Grøttum & Beveridge, 2007; LaPatra & MacMillan, 2009). Similarly, use of antibiotics per t of salmon produced in British Columbia has decreased by 84% between 1995 and 2008 (Watson, 2011). While the initial response to the emergence of a new bacterial disease in farming is the use of an effective antimicrobial (which is registered for use in food animals), generally, the development of vaccines for significant bacterial diseases quickly follows.

Table 5. Regulations and BMP for the use of chemicals and therapeutants. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Records of all therapeutants used must be kept including quantities and times of use. • Antibiotics must only be used to treat bacterial infections, and not as a growth promoter.	(GAA, 2011)
Global ASC salmon standard	• Records of all therapeutants must be kept including quantities and times of use. • Antiobiotics must not be used as a prophylactic. • No antibiotics or chemicals are to be used that are banned in any of the major salmon producing or importing countries. • Maximum number of antiobiotic treatments per production cycle is 3. • Buyers must be provided with a list of all therapeutants used to treat fish. • Nets treated with Cu-based anti-foulants must not be cleaned or treated *in situ*, but cleaned on a land site with an effluent treatment system. • Cu sediment concentrations in the AIZ[13] must be <34 mg kg^{-1} (DW) or the same as the reference sites. • Biocides used as anti-foulants must be approved for use in Australia, USA or the European Union. • Cumulative parasitic treatment index (PTI) must be ≤13[14].	(ASC, 2012)
Norway	• Records of all chemicals, therapeutants and anti-foulants used must be kept including quantities and times of use. • Must post public notice of antibiotic use. All fish treated with antibiotics in the 12 mths prior to slaughter are tested for antibiotic residues prior to slaughter. • Only permitted chemicals and therapeutants are allowed to be used to treat fish. • Therapeutants must be ordered through a veterinarian. • No harvesting is permitted until after the withholding period and there is a zero detection limit for any therapeutants.	(Maroni, 2000; Wilson *et al.*, 2009)
Scotland	• Only chemicals and therapeutants permitted under European and UK legislations may be used to treat fish. • Records of all chemicals and therapeutants used must be kept including quantities and times of use. • Withholding periods for chemicals must be adhered to. • Only approved anti-foulants may be used. Tributyltin is banned as an anti-foulant. • *In situ* washing of Cu-impregnated nets is prohibited.	(Braithwaite & McEvoy, 2005; FAO, 2005a; SFAWG, 2006; Grøttum & Beveridge, 2007)
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• BC: Records of all chemicals, therapeutants and anti-foulants used in the farm must be kept including quantities and times of use. • BC: Only 3 lice treatments permitted per production cycle. • NB, NS: Nets must not be chemically disinfected on site. Only permitted chemicals may be used to disinfect equipment. Disinfection on land must not be conducted near waterways or standing water.	(Government of New Brunswick, 2006; Watson, 2011; Cohen, 2012)
USA (Washington (WA),	• ME: Must post public notice of theraputant use. • ME: Only permitted chemicals and therapeutants allowed to be used	(Washington Fish Growers Association,

[13] 55 m radius from net-pens
[14] See ASC (2012) for calculation of PTI

Country	Regulations	Reference
Maine (ME))	in the sea. Authorities must be notified within 30 days of theraputant use. Use of chemicals must be kept to a minimum and must not have an adverse effect on the environment. • ME: No discharge of disinfectants in the sea. • ME: Application of biocidal chemicals on site is prohibited. Tributyltin is banned as an anti-foulant. • WA: Records of all antibiotics used must be kept including quantities and times of use. • WA: Records of anti-foulants used must be kept. • WA: Only licensed therapeutants should be used, which are administered by veterinarians.	2002; SMDEP, 2008; Wilson *et al.*, 2009)
Australia (South Australia (SA), Tasmania (T))	• SA: Records of all chemicals and therapeutants used must be kept including quantities and times of use. • T: Antibiotics, anti-foulants or other chemicals used must comply with environmental standards. No detectable chemical or therapeutants residues are permitted beyond the farm area. • SA: Only registered or prescribed chemicals may be used as anti-foulants, therapeutants or disinfectants.	(Aquaculture Act, 2001 (SA); Productivity Commission, 2004; FAO, 2010)
New Zealand	• Records of all chemicals used in the farm must be kept including quantities and times of use. • Tributyltin is banned as an anti-foulant. • Use of antibiotics requires a resource consent. • Only regulated chemicals and therapeutants permitted to be used. • Use of chemicals and therapeutants shall be minimised and must be suitable for use.	(Hazardous Substances and New Organisms Act, 1996 (NZ); Agricultural Compounds and Veterinary Medicines Act, 1997 (NZ); NZ Salmon Farmers Association Inc, 2009; Wilson *et al.*, 2009; M. Gillard, NZKS, pers. comm.)

2.7 FISH HEALTH MANAGEMENT

Mass mortalities from disease outbreaks can cause major economic losses in finfish farms. The prevention of disease through good environmental management and operational procedures are the best methods of fish health management. Stressed fish are less able to tolerate other stressors and are more susceptible to disease. The production of disease-resistant genetic families and vaccination of smolts have been used extensively in Europe to reduce the incidence of disease in farmed salmon (Stewart, 1998).

2.7.1 Environmental monitoring for fish health

Dissolved oxygen

Producers need to ensure that environmental rearing conditions e.g. dissolved oxygen, water temperature and toxic algae concentrations, are within the optimal range for the cultured species, which requires regular monitoring (and action if necessary). Sub-optimal environmental conditions and excessive handling will stress fish, reducing their growth rates and making them more susceptible to diseases. Multiple stressors should be avoided and feeding should be withdrawn 2–3 days prior to handling to minimise respiratory stress (Thomson & Side, 2002).

Salmon have a high oxygen requirement and the recommended minimum dissolved oxygen concentration is 6 mg l^{-1} (~60% saturation at 16 °C) (Brooks *et al.*, 2002; Remen *et al.*, 2012). Dissolved oxygen concentrations below 6 mg l^{-1} are defined as hypoxic for salmon because they cause a decrease in blood oxygen, chronic stress and reduced growth (Mansour *et al.*, 2008; Burt *et al.*, 2012; Remen *et al.*, 2012), and dissolved oxygen concentrations below 1.1–2.6 mg l^{-1} are lethal to salmon (Kazakov & Khalyapina, 1981). Even temporary fluctuations below 6 mg l^{-1} have been shown to adversely affect salmon performance (Anon, 2008; Remen *et al.*, 2012). In an experimental study, Atlantic salmon were subjected to fluctuating decreases in dissolved oxygen from 90% saturation to 40–70% saturation for 2 h every 6 h over a 21 day period. At 90:70% saturation salmon showed a reduced appetite, at 90:60%, 90:50% and 90:40% saturation fish showed general physiological stress responses, and at 90:50% and 90:40% saturation overall growth was significantly lower and some mortality was observed (Remen *et al.*, 2012). These results indicate that minimum dissolved oxygen concentrations should be >70% saturation[15] for optimal growth, and should be >60% saturation[16] for the welfare of the fish.

Aquaculture regulations stipulate that dissolved oxygen concentrations must always be ≥6 mg l^{-1} in Tasmania and Maine and ≥7 mg l^{-1} in Scotland (Table 4). The other countries reviewed have no mandatory requirement to maintain adequate dissolved oxygen levels, and dissolved oxygen concentrations in commercial net-pens in Norway and Canada have been found to be as low as 30–40% saturation at times, despite dissolved oxygen concentration of 80–100% saturation outside the pens and relatively low stocking densities of 9 kg m^{-3} (Anon, 2008; Burt *et al.*, 2012). Thus, it is important to frequently monitor dissolved oxygen concentrations inside the net-pens to check that dissolved oxygen concentrations do not drop below the minimum limit. Dissolved oxygen should ideally be measured continuously at several depths and locations within the net (Oppedal *et al.*, 2011a). If dissolved oxygen concentrations regularly drop below 6 mg l^{-1}, farmers should consider reducing stocking density, cleaning nets more frequently to increase water flow, reducing feeding or relocating the net-pens.

[15] 70% saturation corresponds to 7.6, 7 and 6.6 mg l^{-1} at 12, 16 and 18 °C, respectively (U.S. Geological Survey, 2011).
[16] 60% saturation corresponds to 6.5, 6 and 5.7 mg l^{-1} at 12, 16 and 18 °C, respectively.

Temperature

Water temperature directly affects the growth of fish because it regulates their metabolism and appetite, and fish growth is usually positively correlated to temperature up to a thermal maximum (Blaxter, 1992). When temperatures are too low fish will cease eating and when temperatures are too high fish will become stressed and eventually die. Optimal rearing temperatures for Chinook salmon are between 12–17 °C, with an optimum at 15 °C (Brett *et al.*, 1982; Independent Science Group, 1996; McCullough, 1999). At temperatures above 15 °C growth was reduced and mortality rates increased (McCullough, 1999). Sub-lethal stresses occurred in fish reared at 18–19 °C and growth ceased at 21.4 °C (Brett *et al.*, 1982). The upper lethal temperature for Chinook salmon is 24–25 °C (Brett, 1952; Orsi, 1971; Burck, 1993; Richter & Kolmes, 2005).

Harmful algae blooms

Blooms of toxic algae (e.g. *Heterosigma akashiwo, Cochlodinium fulvescens, Chrysochromulina hirta, Chrysochromulina* spp. *Chattonella* spp., *Alexandrium catenella, Dictyocha fibula, Pseudochattonella* spp., *Gymnodinium* spp., *Alexandrium* spp., *Cochlodinium* spp., and *Pfiesteria* spp.) have the potential to adversely affect cultured fish and may cause mass mortalities of farmed fish (MacKenzie, 1991; Heil *et al.*, 2001; Whyte *et al.*, 2001; Martin *et al.*, 2006; MacKenzie *et al.*, 2011; Haigh & Esenkulova, 2012). Blooms of non-toxic algae (e.g. *Chaetoceros* spp.) may also severely stress fish and cause mortalities owing to gill clogging and asphyxiation (Maclean, 1993). Methods routinely applied to mitigate the effects of harmful algae blooms on cultured fish include surrounding the perimeter of cages with tarpaulins and pumping deeper, colder water up to the cages, using airlifts or air-curtains, lowering the pens during surface blooms (requires submersible cages) (Whyte, 1999), and the addition of clay which binds with harmful algae causing them to settle out of the water (Sengco & Anderson, 2003). Towing the cages away from recognised blooms has also been used, particularly when *in situ* techniques are not applicable.

Harmful algae blooms have the potential to cause serious economic losses to New Zealand’s aquaculture industry and as a result the Ministry of Fisheries along with the aquaculture industry have developed a comprehensive harmful algae blooms monitoring programme, with weekly phytoplankton samples taken from numerous sites around the country, including several sites in the Marlborough Sounds (Marlborough Shellfish Quality Programme) (Rhodes *et al.*, 2001). This monitoring programme provides an early warning system for the local aquaculture industry allowing farmers to harvest stock where possible prior to the bloom reaching the farming site. Provision of strategically placed emergency farm sites or fallowed sites would provide alternative locations that fish farms may be shifted to during localised harmful algae blooms to minimise fish stress and mortalities.

2.7.2 Aquaculture Management Area Agreements, single-year class production and fallowing.

Many salmon pathogens do not survive long without a host (Thomson & Side, 2002), and therefore, the temporary removal of all salmon from an area is an effective way of disease control. Regulatory authorities in some countries are beginning to introduce Aquaculture Management Area Agreements (AMAA), which co-ordinate operational procedures among neighbouring farms such as production cycles, year-class rotations, fish stocking limits, biosecurity protocols, fallowing cycles and disease control. Currently, New Brunswick, Maine and Scotland have AMAA in operation (Scottish Executive, 2000; MAA, 2002; Chang *et al.*, 2007).

AMAA combined with single-year production and fallowing have shown to be effective at controlling disease outbreaks. Total mortality on fallowed salmon farms was significantly lower than mortality on non-fallowed farms (20% vs. 30%, respectively) (Wheatley *et al.*,

1995) and since the introduction of AMAA in Scotland in 2000 there has been no major outbreaks of ISA (Scott, 2010).

AMA need to be sufficiently separated from one another to prevent the transfer of pathogens between areas, and ideally, should be consistent with hydrographically defined boundaries to effectively prevent disease transmission. For example, New Brunswick was initially divided into 21 AMA[17] with a 2-year rotation system. However, it was found that these AMA were not effective in preventing the transmission of ISA. In 2006, hydrographical modelling data were used to amalgamate the 21 AMAs into 3 larger AMAs that had minimal overlap of mixing zones, and a 3-year rotation with mandatory fallowing was implemented to reduce the transmission of ISA (Chang *et al.*, 2007). Since implementation of the new AMA scheme there have been no further ISA outbreaks in New Brunswick (Chang & Page, 2010).

Fallow periods required to break a disease cycle are relatively short (1–3 months), but must be combined with single-year class production to prevent transmission between year classes. For example, smolts in a multi-class stocked farm were found to be infected with sea lice within 3 days of stocking and required anti-parasitic treatment within 4 weeks of stocking. However, when the farm was fallowed for 6 weeks and then only stocked with smolts, fish did not required anti-parasitic treatment until 8 months post-stocking (Stewart, 1998).

Table 6. Regulations and BMP for fish health management. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Water temperature, salinity and DO must be monitoring at least daily. • Fish condition and behaviour should be inspected daily. Staff reports on fish health shall be investigated by a fish health professional. • Records of disease outbreaks and mortalities must be kept, including treatment, fish condition, and number and total weight of dead fish. • DO conditions must be ≥80% saturation during live fish transport. • Fish must be stunned humanely before slaughter. • All smolts must be free of diseases and parasites and vaccinated (where available) before being introduced onto the farm. • Farms must comply with AMAA Fish Health Management Plans (FHMP) if they are a member, or with other neighbouring BAP certified farms.	(GAA, 2011)
Global ASC salmon standard	• Farms must participate in AMAA. If no AMAA is currently in existence, farmers must work towards establishing one. • Farms must comply with AMAA regarding disease management, fallowing, production cycles, and information sharing. • Fish must be regularly inspected for sea lice (weekly during sensitive periods) and infestation rates must be publicly available. In areas with wild salmonids, <0.1 mature female sea lice per farmed fish is permitted during sensitive periods (e.g. during juvenile out-migration). • Farms must have a FHMP and be inspected by a veterinarian at least 4 times per year. • All mortalities must be recorded. A post-mortem analysis must be conducted for all mortality events. Dead fish must be disposed of in a responsible manner. • The presence of any suspected unidentifiable disease agent or unexplained increases in mortality must be reported. • Viral-related mortalities must be ≤10% in the latest production cycle.	(ASC, 2012)

[17] Called Bay Management Areas in New Brunswick

Country	Regulations	Reference
	• If mortality rate is >6% in a production cycle, ≤40% of mortalities are to be unexplained. • If a World Organisation for Animal Health (OIE)-notifiable disease is confirmed on the farm than all fish in infected pens must be culled, other farms in the AMA must be notified and increased disease monitoring must be conducted. • All smolts must be free of diseases and parasites and be vaccinated (where available) against significant diseases in the area before being introduced onto the farm.	
Norway	• Mandatory sea lice monitoring (every 14 days), reporting and auditing. • All farmed fish must be vaccinated where effective vaccines are available. • Management Plans must be approved by Animal Health Authority. • Must keep records of disease outbreaks, diagnoses, testing, treatment and number of fish slaughtered. • Regular health control by a qualified person must be carried out at fish farms according to guidelines issued by the Animal Health Authority. • Equipment must be disinfected before use. • Mortalities must be disposed of correctly. Fish must not be slaughtered on the farm. • Farmed fish parts must not be fed to other farmed fish.	(Maroni, 2000; Dow, 2004; Wilson *et al.*, 2009)
Scotland	• Mandatory registration of facilities, reporting of prescribed diseases and treatment procedures, movement of stock on/off farm, and harvest/disposal of infected stock. • In parasite-infested regions the movement of stock and equipment may be prohibited, mandatory treatment or immediate slaughter stipulated. • Regulatory authority conducts parasite monitoring and may require farmers to implement control measures. • Certain notifiable diseases must be reported to the authorities. • Compliance with industry's Code of Practice to avoid and minimize the impact of ISA is monitored by government audit/survey. • Diseased or dead fish must not be transported with live fish. • Multiple-year classes should not be co-cultured to reduce the risk of disease transmission. • Farm sites should be fallowed for 4 weeks after each rearing cycle to prevent pathogen transfer. • All equipment used should be appropriately disinfected.	(FAO, 2005a; SFAWG, 2006; Aquaculture and Fisheries Act, 2007 (Scotland))
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• BC: Mandatory sea lice monitoring, reporting and auditing. • BC: Mass mortalities of >4000 kg must be reported immediately • BC: Requires comprehensive FHMP for all aquaculture operations. FHMP must contain plans for routine disease monitoring, record keeping of health status, and preventing, controlling or treating disease. FHMP specify operators must: employ resources/personnel to effectively address fish health issues; have rapid response plans for disease events; detail all monitoring activities, including those focusing on the effectiveness of treatments and controls, and notify authorities of disease outbreaks. • BC: Fish stress must be minimised when handling fish. • Mortalities must be disposed of correctly. • NB: Regulations address mortality handling and health monitoring. • NB: Single-year class entry operating practices required.	(Dow, 2004; Cohen, 2012)
USA (Washington (WA), Maine (ME))	• WA: Disease control regulations require establishment of disease control policies. All serious pathogen outbreaks must be addressed immediately and reported to authorities within 2 working days.	(Washington Fish Growers Association, 2002; SMDEP,

Country	Regulations	Reference
	• ME: Regulatory authority to collect data on disease incidents and use of therapeutants. • ME: Dead fish must be removed from pens once per week • WA: Fish handling will be kept to a minimum. Fish condition will be regularly inspected and dead/dying fish removed promptly and disposed of in a responsible manner. • WA: Fish will be transported in waters with adequate DO.	2008)
Australia (South Australia (SA), Tasmania (T))	• Mandatory reporting of prescribed diseases and treatment procedures and harvest/disposal of infected stock. • T: Compliance with all environmental reporting requirements including suspect or known incidents of disease or mortality affecting >0.25% of fish per day for three consecutive days in any individual net-pen. • SA: Any unusually high, unexplained mortality over a 24 h period must be reported to the minister immediately and all reasonable steps must be taken to isolate affected fish.	(Aquaculture Act, 2001 (SA); FAO, 2010)
New Zealand	• Producers are required to take all reasonable steps to ensure that the physical, health, and behavioural needs of the animals are met in accordance with both good practice and scientific knowledge. • Authorisation is required to move fish from freshwater hatcheries to marine sites. • Certain notifiable diseases and organisms must be reported to the authorities within 24 h. • Fish infected with notifiable organisms must not be sold. • Fish must be inspected on a daily basis for signs of stress or other abnormalities, feeding behaviour and presence of predators. Immediate remedial action is required in unsatisfactory situations. • Every farm shall undergo an annual disease inspection conducted by a certified pathologist using accepted procedures. • Mortalities should be removed at least twice a week. All mortalities must be counted and recorded, including the likely cause of death. • Mortalities must be disposed of in a way that does not cause hazard to other stocks, wildlife or humans. • Staff shall be trained to recognise fish health problems. • Veterinary examinations should be made where there are abnormal, unexplained mortalities. • Producers must comply with approved biosecurity practices. • Diseased fish must not be transported. Records of mortalities or injuries that occur during transport must be kept.	(Freshwater Fish Farming Regulations, 1983 (NZ); Biosecurity Act, 1993 (NZ); Animal Welfare Act, 1999 (NZ); NZ Salmon Farmers Association Inc, 2009; Biosecurity (Notifiable Organisms) Order, 2010)

2.8 ESCAPE PREVENTION

Escapes of cultured fish because of equipment failure, predator attacks or handling errors can cause large economic losses, and therefore, producers generally take all practical steps to prevent escapes. Legislation in the northern hemisphere is highly focused on escape prevention because there is much concern that escaped cultured fish will alter the genetic variability of wild populations or act as disease vectors. In New Zealand and Australia there is no true potential for genetic interactions with 'wild' fish because all Salmonidae are non-native and Salmonidae do not inter-breed with indigenous species (Wilson *et al.*, 2009).

Development of commercial marine farming of indigenous species in New Zealand will require consideration of the risk for genetic impact on wild stocks. Potential risk factors could include marked loss of heterogeneity in the farmed stock, severely reduced wild populations such that domestic stock contribution would contribute significantly to the breeding population, escape of gametes from mature farmed stocks, and escape of farmed fish. Two indigenous fish species are currently under development, hapūku *(Polyprion oxygeneios)* and yellowtail kingfish (*Seriola lalandi*). The risk of genetic impact to wild stocks has been reduced by retaining the heterogeneity of the cultured stock. Furthermore, the anticipated harvest size for hapūku and yellowtail kingfish currently precedes the age or size of maturation so there will be little chance of released gametes from farmed stock. Given the current size of wild stocks and New Zealand fisheries management, any escapes would be substantially diluted by the established wild populations (Bekkevold *et al.*, 2006; Jensen *et al.*, 2010; Uglem *et al.*, 2012).

Table 7. Regulations and BMP for fish escape prevention. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Farms must do everything practical to prevent escapes including staff training, compliance with minimum equipment standards, regular equipment inspections, written fish handling procedures and predator control measures. • All escapes are to be reported. • BAP certification is suspended if there are 3+ escapes of 500+ fish in one production cycle, or a single escape of 5000+ fish.	(GAA, 2011)
Global ASC salmon standard	• Farms must do everything practical to prevent escapes including staff training, compliance with minimum equipment standards, regular equipment inspections, written fish handling procedures and predator control measures. • <300 escapes permitted in most recent production cycle.	(ASC, 2012)
Norway	• Staff training required and operation/maintenance of facilities to prevent escapes. • All equipment, materials and structures must be designed, constructed, installed, inspected and maintained to prevent escapes. • Records of escapes must be kept and immediate notification must be made to the authorities. • Recapture efforts must follow escape events. • Farms must deploy prescribed nets at 20 m distance from farms from Oct–Apr to monitor for escapes. • Minimum net-strength standards are in place.	(Maroni, 2000)
Scotland	• Escapes may be treated as an offence depending on circumstances. • Escapes must be reported to authorities within 24 h. • All nets, equipment and handling procedures should be designed to minimise the chance of escapes. Equipment should be inspected and maintained regularly.	(SFAWG, 2006)
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• BC, NB: Escapes absolutely prohibited under legislation. • BC: Reporting of actual and suspected escapes required within 24 hours, and in writing within 1 week. • All equipment, materials and structures must be designed, constructed, installed, inspected and maintained to prevent escapes. • BC: Staff training required and operation/maintenance of facilities to prevent escapes. All net handling practices must be documented in BMPs. Written escape response plans required. • BC: Detailed anchoring/structural plans required. • BC: Daily inspection & record-keeping mandatory. • BC: Inspections following events that may stress containment structures	(Government of New Brunswick, 2006; Cohen, 2012)

Country	Regulations	Reference
	is mandatory. • BC: Comprehensive minimum net-strength standards. Only jurisdiction to require minimum net inspection schedule over the lifetime of the net. • BC: Reasonable measures to recapture escaped fish required. • NB, NS: Nets must be changed at the beginning of each production cycle, or more frequently if required.	
USA (Washington (WA), Maine (ME))	• WA: Escapes may be treated as an offence depending on circumstances. • WA: “Significant” escapes (3000 or more fish of 1 kg or less in size; 1500 fish of 1 kg or more) must be reported within 24 h. Annual escape reports must be submitted. • ME: Escapes of 50+ fish ≥ 2 kg must be reported within 24h. Records of all other escapes must be kept. • ME: All equipment, materials and structures must be designed, constructed, installed, inspected and maintained to prevent escapes. • WA: Contingency planning for escape events is required.	(Aquaculture Lease Regulations, 1983 (Maine); Washington Administratrative Code, 2003)
Australia (South Australia (SA), Tasmania (T))	• SA: Must have a written plan for minimising escapes. All equipment to be well-maintained and must comply with minimum equipment standards. • T: Escapes may be treated as an offence depending on circumstances. • T: Escape reporting required for the loss of >1000 fish to the marine environment at any one time. • Any significant incident of fish escapes must be reported to the authorities within 12–24 h of becoming aware of the escape.	(Aquaculture Act, 2001 (SA); FAO, 2010)
New Zealand	• No requirements to report escapes. • Farm structures must be capable of withstanding the weather and environmental conditions on the site to ensure containment of the fish. • Equipment must be regularly inspected and maintenance records must be kept. • Escapes or near escape incidents must be recorded. • Producers must have contingency plans to cover events where there is damage to structures that could lead to fish escapes. • The mesh size and gauge of nets must be sufficient to contain the smallest fish stocked.	(NZ Salmon Farmers Association Inc, 2009; M. Gillard, NZKS, pers. comm.)

2.9 INTERACTIONS WITH WILD ANIMALS

The apparent availability of a concentrated source of food means that fish-eating birds, sharks and mammals will inevitably try to get inside net-pens to eat the fish. Hence, there is a risk of predators getting entangled in nets or ropes, and/or causing damage to the nets allowing fish to escape. Other possible negative effects of the proposed activity on marine mammals, sharks or seabirds include; the loss of foraging space or the disruption of foraging activity, the disruption of breeding activity, and possible changes in prey abundance because of changes to the benthic community (Lloyd, 2003). All six countries reviewed have a duty to report any interactions with large marine mammals (Table 8).

Table 8. Regulations and BMP for interactions with wild animals. Statutory regulations are listed in black and recommended BMP are in blue. Where there are differences in regulations among different jurisdictions within a country (Canada, the USA and Australia), these have been separated by jurisdiction.

Country	Regulations	Reference
Global GAA salmon standard	• Farms must have a written plan for minimising adverse effects on wild animals. • Non-lethal control measures are to be used where possible. If lethal control measures are necessary then they must be humane. Endangered or International Union for Conservation of Nature (IUCN) red list species must not be killed. • All seabird, mammal and reptile mortalities must be recorded. • Acoustic deterrents may only be used if they are verified (by an expert) not to harm endangered cetaceans.	(GAA, 2011)
Global ASC salmon standard	• Non-lethal control measures are to be used where possible. If lethal control measures are necessary then they must have prior approval from the relevant authority. Information on lethal incidents must be publicly available. • <9 lethal incidents are permitted per year, of which, ≤2 are to be marine mammals. Endangered or IUCN red list species must not be killed. • Acoustic deterrents must not be used for >40% of the production cycle. Acoustic deterrents will not be permitted after 2015 unless they have been demonstrated not to harm marine mammals.	(ASC, 2012)
Norway	• Limited culling of seals and otters permitted if non-lethal methods fail to deter predators. All culls must be reported.	(CERMAQ, 2012)
Scotland	• Application to slaughter birds must be made to the authorities. • Seals must not be shot without a licence or during the closed season. • If slaughter of predators is necessary, it must be humane. • Fish should be protected from predators by exclusion nets or other anti-predator devices.	(SFAWG, 2006; Marine Act, 2010 (Scotland))
Canada (British Columbia (BC), Nova Scotia (NS), and New Brunswick (NB))	• BC: Records of predator control methods must be kept. • BC: Any accidental drowning of marine mammals must be reported. • BC: Any incidental catches of other species must be recorded. • Culling of seals and sea lions permitted under licence if they endanger human life or the aquaculture facility. All culls must be reported to authorities.	(CERMAQ, 2012; Cohen, 2012)
USA (Washington (WA), Maine (ME))	• WA: Records of interactions with wild mammals or seabirds must be kept. • WA: Predators will be controlled using legal, non-lethal methods. • WA: No transgenic salmon will be farmed.	(Washington Fish Growers Association, 2002; Wilson *et al.*, 2009)
Australia (South Australia	• T: Regulatory compliance with marine and wildlife management standards is required.	(Aquaculture Act, 2001 (SA);

Country	Regulations	Reference
(SA), Tasmania (T))	• SA: Must have a written plan for minimising adverse effects on seabirds or large marine vertebrates. • SA: Records of any interactions with large marine vertebrates must be kept.	FAO, 2010)
New Zealand	• Accidental deaths of mammals must be reported. • Only non-lethal control methods may be used for mammals. Control permit must be obtained from the Department of Conservation (DOC). • Use of genetically modified or transgenic brookstock is prohibited. • All measures must be taken to minimise the entanglement of wildlife. Accidental ensnarement of marine mammals must be promptly reported to DOC. • All personnel handling seals must hold the relevant unit standards.	(Marine Mammals Protection Act, 1978 (NZ); Marine Mammals Protection Regulations, 1992 (NZ); NZ Salmon Farmers Association Inc, 2009)

3 Benefits of the implementation of BMP

Limited published information is available on measured economic or environmental benefits of implementing BMP. Furthermore, many BMP are implemented simultaneously, and therefore the benefits of individual BMP are unknown. Three examples are given below on the benefits of implementing various BMP.

Increased smolt efficiency

Culture of Atlantic salmon in Ireland has seen a 40% reduction in the number of smolts stocked per t of salmon harvested between 1985 and 1995. This decrease in smolts per t salmon was largely attributed to:

1. Improvements in smolt quality through genetic breeding programmes and vaccination;
2. The implementation of fallowing and single-year class production to reduce the incidence of disease and therapeutants use, and;
3. Reduction in the FCR ratio by 50% through better feed development and management (Stewart, 1998).

These industry improvements produced a number of environmental and economic benefits including:

1. Lower smolt production costs per t harvested;
2. Higher growth rates due to improved feed quality and husbandry;
3. Less individuals and lower standing biomass required per t harvested;
4. A reduction in the amount of therapeutants required because of lower stocking densities, fallowing and single-year class production;
5. A reduction in organic waste produced because of better FCR, feed management and a reduction in standing biomass;
6. Shortened production cycle because of higher growth rates, resulting in increased fish survival and labour efficiency (Stewart, 1998).

Reduced environmental impact from organic waste

Farm location can have a great impact on the level of environmental impact caused by fish farms. In one example, a Canadian fish farm was relocated after its first year of production to a site 70 m away that had higher flow rates. Free sulfide concentrations in the second year decreased by 58% and 91% directly under the farm and 30 m from the farm, respectively, while annual production increased by 12% (Backman *et al.*, 2009).

Implementation of fallowing and improved feed management has also been shown to reduce the environmental impact of salmon farms on the environment. For example, free sulfide concentration under a commercial salmon farm in Canada was found to frequently exceed the maximum limit of 6000 µM. Mitigation measures were implement including a 2–3 month fallowing period after each production cycle, a reduction in maximum production by ~40%, and a change in the feeding regime from continuous small doses to carefully regulated, larger ‘meals’. These combined mitigation measures resulted in the farm attaining compliance for three consecutive years, and a reduction in average free sulfide concentrations from 6370 µM to 3650 µM over a 4 year period (Backman *et al.*, 2009).

Reduced production costs

Production costs in Norway for farmed salmon have decreased by around 70% over the last 20 years from around NZ$10.80 kg^{-1} (€6.80) to NZ$3.20 kg^{-1} (€2.00) (Grøttum & Beveridge, 2007). This reduction in production costs is largely attributed to improvement of fish through genetic breeding programs, decreased mortality from widespread vaccination use, improved fish feed development and the reduction of fishmeal and fish oil in feeds, and better efficiencies from upscaling production (Grøttum & Beveridge, 2007).

4 Current New Zealand aquaculture practices and potential BMP for New Zealand marine finfish farms: a case study of the New Zealand King Salmon Company

Currently, Chinook salmon is the only finfish species cultured on a commercial-scale in New Zealand. There are 12 hatcheries/freshwater sites located in the Canterbury region and 14 marine on-growing sites located in Marlborough Sounds, Stewart Island and Akaroa (Rimmer & Ponia, 2007). Juvenile salmon spend 8–13 months in freshwater hatcheries before being transferred to sea farms. Fish are harvested after 19–31 months in the sea farms, at sizes of between 3.5 and 6 kg (New Zealand Salmon Farmers Association, 2011).

The New Zealand King Salmon Company (NZKS) is the largest salmon producer in New Zealand, producing around 62% of the country's salmon (Gillard, 2012). Information in the following sections (4.1–4.7) describes NZKS's current operational procedures based on publicly available information and interviews with NZKS, and identifies areas where improvements may be made to improve the economic and environmental performance of the farms. Other salmon producers in New Zealand may have different operational procedures. Freshwater salmon culture is not discussed in this report because the scope of the report is limited to marine finfish culture.

4.1 FARM LOCATION

Aquaculture consents in New Zealand are considered separately and there is no legislated minimum distance between farms. NZKS has eight marine farms in the Marlborough Sounds (Waihinau, Forsyth, MFL48, MFL32, Ruakaka, Otanerau, Clay Point and Te Pangu), five of which are currently in use (Fig. 1). The company has recently gained approval from the Environment Protection Authority for four new farms, but these farms are currently under appeal (Fig. 1).

Forsyth, MFL48, MFL32 and Ruakaka are located in low-flow environments (<4 cm s^{-1}), Waihinau and Otanerau are located in moderate-flow environments (6–9 cm s^{-1}), and Clay Point and Te Pangu are located in high-flow environments (15–20 cm s^{-1}) (Dunmore & Keeley, 2012b; 2012a; Dunmore *et al.*, 2012a; Dunmore *et al.*, 2012b; Dunmore *et al.*, 2013a; Dunmore *et al.*, 2013b; 2013c; Dunmore *et al.*, 2013d). High water temperatures (>17 °C) and low dissolved oxygen (<6 mg l^{-1}) are a problem at MFL48, MFL32, Otanerau and Ruakaka during summer, and to a lesser extent, at Waihinau and Forsyth (Gillard, 2012). The combination of low water currents, high temperatures and low dissolved oxygen are likely to cause respiratory distress, reduced growth and increased stress and mortality in the fish. These sub-optimal conditions are likely to be responsible for the increase in mortality rates during summer, with average summer mortality rates of around 5% (Gillard, 2012; Wardle, 2012). NZKS is currently not using the MFL48, MFL32 or Otanerau sites during summer because of their sub-optimal conditions. The company also tries to reduce mortality caused by these sub-optimal conditions by not stocking smolts at the warmer sites (Waihinau, Forsyth, Ruakaka and Otanerau) until after Christmas when the water temperatures drop. Prior to Christmas, smolts are initially stocked at the cooler sites e.g. Te Pangu, and then towed to the warmer sites in April/May. However, movement of fish between farms is not ideal because it stresses the fish and increases the potential for disease transfer between sites.

4.2 PRODUCTION AND STOCKING

NZKS predominantly use a variety of small (20 × 20 m) to moderate-sized (40 × 40 m) square net-pens that have a depth of 15–20 m. Arrays of up to 20 net-pens are joined together by floating platforms, and predator nets surround the entire array. Circular plastic pens, 60–80 m in circumference, are used at MFL48 and MFL32 (Preece, 2012b). Research has shown that water flow inside net-pens is greatly reduced when it must pass through multiple nets (and the attached bio-fouling) (Fredriksson *et al.*, 2007; Klebert *et al.*, 2013), and therefore, this report recommends that the largest possible nets are used within the current infrastructure and resource conditions. Orientation of the net-pen array so that the longest axis is perpendicular to the predominant water current will minimise the reduction in water flow in the downstream net-pens. However, current resource consent conditions greatly restrict the ability to move existing net-pens within a site or to replace the current structures with alternative net-pens. A double row of individually sited circular net-pens is proposed for the new farm at Papatua and this report recommends that the position of the net-pens are staggered between the two rows.

The NZKS farms are located in relatively shallow waters, with depths of 19–40 m (Preece, 2012a). At some of these sites, use of a 20 m deep net that is surrounded by a predator net leaves little or no distance between the bottom of the predator net and the sea bed, which is likely to restrict the horizontal dispersal of waste products. A minimum distance of 1–3 m at low water between the bottom of the predator net and the sea bed is stipulated in Australia (Marine Farming Planning Act, 1995 (Tasmania); Aquaculture Act, 2001 (SA)), and a distance of >5 m is recommended for good waste dispersal (Hargrave, 2002). Ideally, finfish farms should be located in water depths of >40 m to ensure good waste dispersal (Belle & Nash, 2008; Gillard, 2012).

Smolts are initially stocked at densities of <1 kg m^{-3} with densities rising to 20–25 kg m^{-3} prior to harvest. There is no legislated maximum stocking density or biomass in New Zealand but NZKS have recently implemented a voluntary maximum stocking density. Generally, multiple-year classes are stocked at each site to maximise productivity. If commercially significant diseases of salmon occurred in New Zealand, then the stocking of multiple-year classes on a single site would increase the risk of disease transmission.

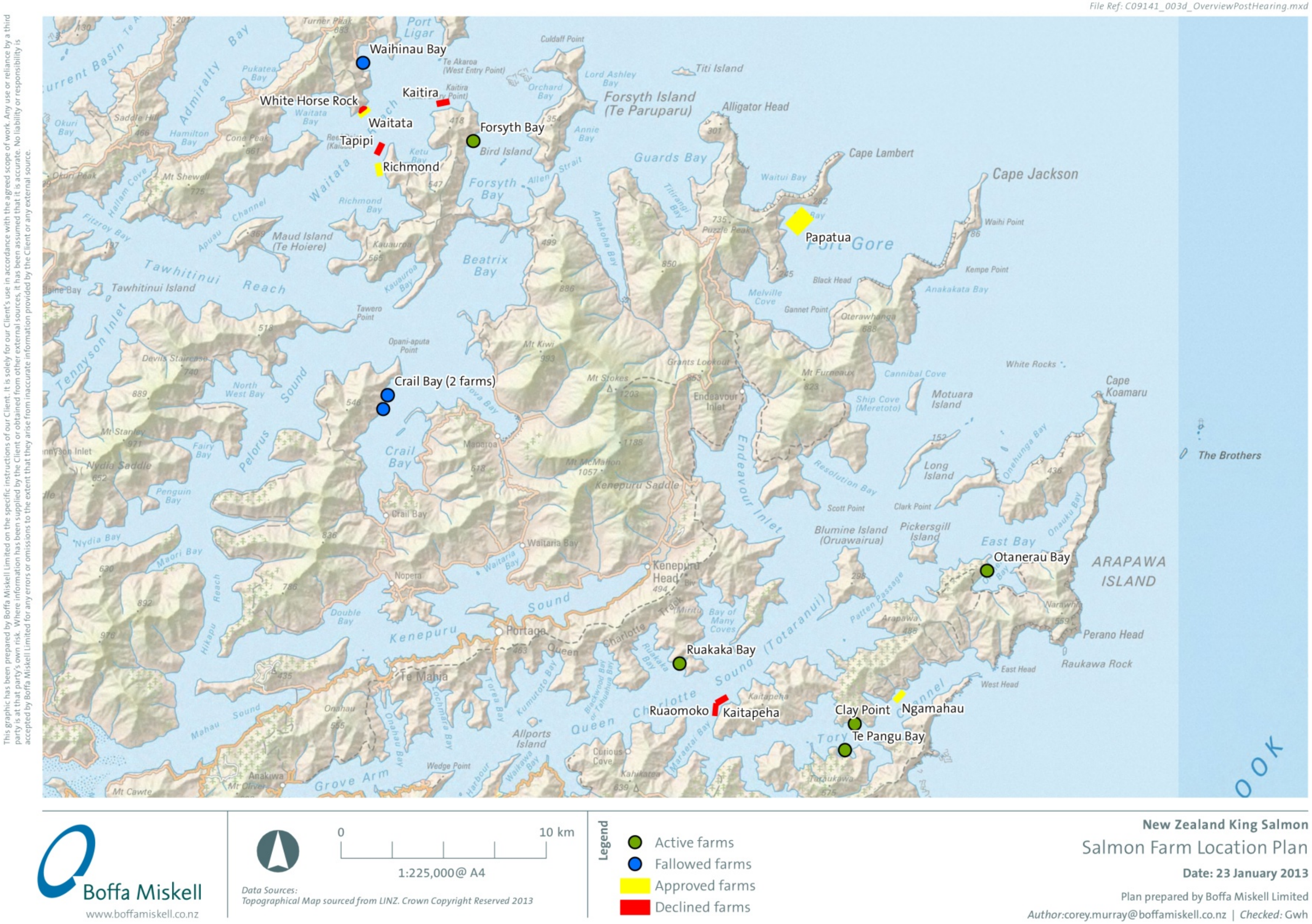

Figure 1. Location of current New Zealand King Salmon farms in the Marlborough Sounds and position of recently approved/declined farm applications by the Environment Protection Authority (Map is reproduced with permission from NZKS)

4.3 FEED MANAGEMENT

Control of organic waste input to the marine environment is primarily controlled through the setting of maximum feed quotas for each site in New Zealand. Maximum feed quotas are reviewed each year based on the level of impact underneath the farms. NZKS are currently not feeding the maximum quota at some sites because the feed levels appear unsustainable at particular sites.

Salmon are fed specifically-formulated extruded pellets, which contain no antibiotics, hormones or growth promotants. In general, smolts are fed 5–6 times per day whereas 2+ year fish are only fed once per day. Fish are demand-fed and underwater monitors deployed at 5 m depth are used to assess the required feeding duration and quantity. Once fish pellets pass by the underwater cameras, feeding is stopped. An assessment of NZKS feed management show that feed wastage is very low at around 0.1% (Preece, 2012b). The average FCR for NZKS fish is 1.8 (Preece, 2012a), which is higher than the industry average for all commercial salmon species of 1.25 (Tacon & Metian, 2008). The higher FCR of Chinook salmon is partially due to the higher oil content of Chinook salmon (Wybourne, 2012), however, it is possible that FCR may be improved with further research on feed development and management.

Zinc is an essential mineral for fish and is present in fish feeds at concentrations between 68–240 mg kg^{-1} (dry weight) (Scottish Association for Marine Science & Napier University, 2002; Dean *et al.*, 2007). Excessively high zinc concentrations in the feed or over-feeding can result in elevated zinc concentrations in the sediments underneath the farms. Concentrations of zinc in the sediment underneath NZKS salmon farms were 67–455 mg kg^{-1} in 2012, with zinc concentrations at two farms exceeding the high-ISQG of 410 mg kg^{-1} (ANZECC, 2000; Dunmore *et al.*, 2012a; Dunmore *et al.*, 2012b; Dunmore *et al.*, 2013a; Dunmore *et al.*, 2013b; 2013c). The negative impacts of elevated zinc concentrations in the sediment below finfish farms are not well understood. It is likely that the majority of zinc in the sediment under farms will bind with sulfides and organic matter, reducing their dispersion and bioavailability (and hence their subsequent toxicity) (Brooks *et al.*, 2003; Burridge *et al.*, 2010). In 2012, NZKS reduced the concentration of zinc in their fish feeds from 160 ppm to 95 ppm and changed to using organic zinc, which has a higher assimilation efficiency than inorganic zinc (Wybourne, 2012). These changes are estimated to decrease the zinc inputs to the environment by around 50% (Wybourne, 2012).

4.4 ENVIRONMENTAL EFFECTS AND WASTE MANAGEMENT

Environmental monitoring requirements differ among NZKS farms depending on the resource consent conditions. For example, the Waihinau site has no monitoring requirements whereas newer sites have extensive monitoring requirements. NZKS has voluntarily opted to monitor all of their sites so that they meet the most extensive requirements. Monitoring requirements generally involve assessment of sea bed impacts, with particular regard to the benthic community, zinc and copper concentrations, and dissolved oxygen concentrations near the seabed. Cawthron Institute has developed an Enrichment Stage (ES) model to assess benthic impacts of NZKS farms, based on a cumulative score of the oxygenation of the sediment, infauna composition and % total organic matter (Keeley, 2012). The criteria for each stage is also dependent on whether the farms are located in a low flow (<9.5 cm s^{-1}) or high flow ($>$ 9.5 cm s^{-1}) environment. An ES score of 1 is indicative of a pristine environment whereas an ES score of 7 is an anoxic environment that is uninhabitable by macrobiota (see Table C in the Appendix).

Comparison of the environmental impact permitted in New Zealand with the other reviewed countries show New Zealand generally has intermediate standards and enforcement measures.

For example, in Tasmania, a greater level of environmental impact caused by finfish farms is generally permitted, with permitted conditions 35 m from fish farms generally similar to the permitted conditions directly underneath fish farms in New Zealand (Bartholomew, 2013). However, in Tasmania farms are not allowed to restock if bacterial mats are present underneath the farms or there is evidence of spontaneous outgassing. In Canada and the USA, where environmental impact is mainly assessed by free sulfide concentrations underneath the farms, free sulfide concentrations must be <6000 µM, and British Columbia producers are not allowed to re-stock their farms until sulfide concentrations are <1300 µM 30 m from the net-pens (Environmental Management Act, 2003 (BC); SMDEP, 2008; Wilson *et al.*, 2009). Using the Northern American criteria, the Otanerau and Te Pangu farms would exceed the permitted sulfide limits[18], and Clay Point and Ruakaka may not be allowed to restock before a fallow period (Dunmore *et al.*, 2012b; Dunmore *et al.*, 2013a; Dunmore *et al.*, 2013c; Dunmore *et al.*, 2013d). In New Zealand, failure to comply with environmental standards generally results in a reduction of feed quota for the following year.

Fallowing of impacted sites is the most commonly utilised method of site remediation and many of the reviewed countries routinely use fallowing and site rotation to manage the environmental impact of finfish farms. Uptake of fallowing and site rotation practices in New Zealand has been limited because of a lack of farm space and resource consent conditions. Licensed farm areas are very small and there is little room to move net-pens within the licensed area. Movement of net-pens in some resource consents is prohibited. Ideally, producers should have available double the farm space that they currently utilise, so that half the sites can be left to fallow for an entire production cycle. This would also provide emergency sites that may be used if required e.g. for relocating fish during harmful algae blooms. Current operating conditions mean that farm sites in New Zealand have no chance to recover, which may result in a gradual decline in environmental conditions and reduced fish production. NZKS have been trialling a 2-yr site rotation between Waihinau and Forsyth since 2011 to allow some remediation of the benthos and sediment, but it is too early to assess the possible benefits of site rotation at these two sites (Dunmore *et al.*, 2012a). At the new Papatua site it is proposed that two rows of individual circular cages will be used within a four-row lease area. The position of the cages will be moved within the farm lease area after every production cycle to allow some remediation of the benthos and sediment (Preece, 2012b). NZKS would like to implement routine fallowing and site rotation at all of their sites, provided that additional farm space is made available, so that they can maintain production volumes (M. Gillard, NZKS, pers. comm.).

4.5 USE OF CHEMICALS AND THERAPEUTANTS

Concentrations of copper in the sediment under finfish farms are often elevated because of leaching from anti-foulants, and at times over the last five years copper concentrations at Forsyth and Ruakaka have exceeded the low-ISQG limit of 65 mg kg^{-1}, and Otanerau and Waihinau have (at times) exceeded the high-ISQG limit of 270 mg kg^{-1} (Dunmore *et al.*, 2012b). Copper concentrations were lowest at the Te Pangu (23 mg kg^{-1}) and Clay Point (51 mg kg^{-1}), which have the highest current speeds. In 2012, NZKS stopped using copper-based anti-foulants on their predator nets[19] and instead removed bio-fouling organisms with high pressure washing *in situ* to try and reduce copper accumulation in the sediment below the farms. Nets are cleaned approximately monthly *in situ*, or are lifted clear of the water and water-blasted at the farm site (Preece, 2012b). Despite the change in bio-fouling management, analyses of copper concentrations underneath the farms in October and November 2012 show mixed results. Copper concentrations at Otanerau, Ruakaka and Te Pangu decreased by around 25–40% from the previous year, but copper concentrations at Clay Point, Waihinau

[18] Sulfide concentrations in 2012 were 6360 µM at Otanerau underneath the farm and 7890 µM at Te Pangu 60 m from the farm.
[19] Anti-fouling paint has never been used on the NZKS grower nets (M. Gillard, NZKS, pers. comm.)

and Forsyth increased, despite Forsyth having been fallowed for 11 months prior to monitoring. It is likely that there was still some copper residue on the nets from previous anti-fouling treatments, and the high pressure washing may have accelerated the leaching of copper from the nets. It would be expected that copper concentrations will gradually decline below the farms if no further copper anti-foulants are applied.

Removal of bio-fouling by high pressure washing *in situ* may also have adverse environmental impacts, particularly in low-flow environments. Accumulation and degradation of bio-fouling organisms underneath the farms may cause a localised reduction in dissolved oxygen and increased eutrophication. In areas with high bio-fouling rates, *in situ* washing may be more detrimental to the environment than application of copper-based anti-foulants (Belle & Nash, 2008). Furthermore, if bio-fouling organisms are not removed frequently enough, fish welfare and growth may suffer because of low dissolved oxygen conditions within the net-pens. This report recommends that in low-flow sites (which are already likely to have sub-optimal oxygen conditions) that nets are removed and cleaned on land where bio-fouling can be collected and disposed of. This is also likely to reduce the amount of residue copper leaching into the environment from previous anti-fouling applications. It is acknowledged that the removal and cleaning of nets on land will generate additional production costs, which will need to be taken into consideration.

To date, fish diseases or parasites have not caused any major loss of life in New Zealand farmed salmon. Antibiotics or therapeutants are not currently used on farmed fish in New Zealand and disinfection of equipment is not routinely conducted.

4.6 FISH HEALTH MANAGEMENT

Given the lack of major disease outbreaks in New Zealand there has been less emphasis place on fish health management in New Zealand than other countries. There is no mandatory requirement to culture single-year classes in New Zealand and multi-year classes are typically cultured at the same site to maximise productivity. Unexplained mortalities are thought to be caused by opportunistic pathogens or environmental perturbation rather than diseases specific to salmon (A. Forsythe, NIWA, pers. comm.). Single-year class production combined with a short fallow period after each production cycle has proven to be very effective in reducing mortality rates in farmed salmon overseas (Wheatley *et al.*, 1995; Chang & Page, 2010; Scott, 2010). NZKS is considering implementing a biosecure fish health management strategy, if necessary, that will divide its farms into three management areas. There will be no movement of vessels or fish among areas and each area will operate on a single-year class production basis with fallowing between production cycles (Preece, 2012b).

4.7 ESCAPE PREVENTION & INTERACTIONS WITH WILD ANIMALS

Escape prevention in New Zealand is not as stringently regulated as in the Northern Hemisphere countries where salmon occur naturally. There is no requirement to report escapes in New Zealand (Wilson *et al.*, 2009; Preece, 2012b). NZKS deploys predator nets around the farms to prevent losses from seal and shark attacks.

It is prohibited to cull marine mammals in New Zealand and any accidental deaths caused by fish farms must be reported to the Department of Conservation. Since finfish farming started in New Zealand in 1982 there have been four recorded incidences of fatal seal entanglements in farm nets, and five recorded fatal dolphin entanglements (Forrest *et al.*, 2007; Cawthorn, 2012). Most of the deaths were caused by the animals getting trapped in the predator net, and one death occurred while a predator net was getting replaced. Subsequent modifications to the design of predator nets, including ensuring that the predator net fully encloses the fish cages, the net is highly-tensioned, and dead fish are promptly removed from the net-pens, have reduced the risk of further casualties; thus the risk of entanglement of marine mammals in nets is considered small (Cawthorn, 2012).

There has only been one recorded incidence of a sea bird getting entangled in marine farms in New Zealand (Lloyd, 2003; Sagar, 2012), but there have been a few incidences of seabirds getting entangled in litter from marine farms (Taylor, 2000). NZKS deploys netting over all their farms to prevent predation of fish by seabirds, and all feed and salmon carcasses are contained in sealed bins to reduce bird attraction. The company has not allowed seabirds to be shot at their farms since 2010 (Preece, 2012a).

In summary, a review of the operational procedures of NZKS has found that the company generally operates in an environmentally conscious manner, which is supported by their recent attainment of GAA Best Aquaculture Practices certification (NZKS, 2013). Comparison of NZKS operational practices with international BMP has identified a number of areas where finfish aquaculture in New Zealand could potentially be improved, which are summarised in Table 9.

Table 9. Current New Zealand salmon aquaculture practices by NZ King Salmon Company Ltd and recommended BMP.

Category	Current practice	BMP
Farm location	• No minimum distance between farms. Each farm site is individually considered by the authorities. • Some current farms are located in sub-optimal environments (low-flows, high temperatures and low DO during summer).	• Farms should be located in sheltered regions but with moderate-high flows, and water temperatures <17 °C. • Water depth under farms should be >40 m.
Production and stocking	• Small to medium square net-pens are used that are joined together in a gridded array. • Stocking densities are <25 kg m^{-3}.	• Larger, individually positioned net-pens will maximise the water flow through the nets. • Rows/arrays of nets in low-flow sites should be positioned with the longest axis perpendicular to the current to maximise water flow. • Rows of individual net-pens should be staggered in relation to the current direction. • Stocking density should be <25 kg m-3 but optimal densities will be site-specific.
Feed management	• Salmon are demand fed and feeding is ceased when pellets fall pass the underwater monitors. Estimated feed wastage is ~0.1%. • Salmon are fed high-quality, extruded pellets manufactured by a reputable company.	• Reduce or stop feeding when DO <6 mg l^{-1} or temperatures >15 °C. • Do not feed during high current periods or near the edge of nets.
Environment and waste management	• Environmental impacts are generally regulated through reductions in maximum feed quota. • No mandatory fallowing requirements. Movement of cages prohibited on some sites. Site rotation practiced at Waihinau and Forsyth farms since 2011. • No minimum clearance between bottom of net and seabed. At some sites the predator net is very close to the seabed.	• Sites are fallowed for 3–24 months between production cycles to allow site remediation. • Site rotation is practiced to maintain production levels. • A minimum distance of 5 m at low water between external nets and the sea bed is recommended to allow good horizontal waste dispersal.
Chemicals and therapeutants	• No Cu-based anti-foulants used on nets since 2012, nets are cleaned *in situ* by high water pressure. • No therapeutants or vaccines currently used on fish. Antibiotic use will require a resource consent.	• Nets in low-flow environments should not be cleaned *in situ* but removed and cleaned on land. • Nets coated with Cu-based anti-foulants should not be cleaned *in situ.* • In areas where bio-fouling rates are high, use of Cu-based anti-foulants may be less of an environmental risk than *in situ* washing.

Category	Current practice	BMP
Fish health management	• Multi-year class production. • DO concentrations sometimes fall to ~5 mg l^{-1} (53% saturation) inside nets pens during summer. • No emergency farm sites available for use in the Marlborough Sounds.	• Where infectious disease risk can be demonstrated, single-year class production should be carried out at all sites with a short fallow period between production cycles to limit disease transmission. The same year-class should be stocked at sites that are situated close to one another. • Vessels or fish should not be transferred between separate year-classes or distant sites to limited disease transmission. • DO concentrations should be ≥60% saturation for fish welfare and ≥70% saturation for optimal growth. • Emergency farm sites are designated by regulatory authorities, which may be used during emergencies e.g. for shifting farms during localised harmful algae blooms.

5 Conclusions

Aquaculture operations in environmentally-conscious, developed countries must now be conducted with consideration of their environmental impact in order to meet government regulations and the social expectations of consumers. A review of the aquaculture regulations in Norway, Canada, Scotland, USA, Australia and New Zealand show a number of common themes:

1. Aquaculture is typically regulated by many acts involving different levels of government and many regulatory authorities, and consequently, approval of new aquaculture development is an expensive and lengthy exercise (OCAD, 2001). The lack of a streamlined application process is particularly a problem in Scotland, Canada and the USA.

2. Many countries are struggling to balance the growth of viable aquaculture industries with the issues of environmental protection and social expectations for the use of water space (OCAD, 2001). This is particularly an issue in New Zealand, where the limits on access to appropriate water space for aquaculture has impeded implementation of recognised best farming practices and limited expansion of the aquaculture industry. There is considerable public consultation of individual aquaculture resource consents in New Zealand, which also results in lengthy (and costly) delays to the producer.

3. In Australia and Scotland the government is required to create marine development plans where aquaculture is permitted. This greatly reduces the time and cost required for new aquaculture applications (within permitted areas) because environmental impact assessments and public consultation requirements of new farms are greatly reduced.

4. Thresholds are present in some countries/jurisdictions (Scotland, USA and Tasmania) where either EIA or consents are not required for aquaculture operations below certain productions thresholds.

5. Legislation in the northern hemisphere countries is very focused on escape prevention, protection of wild salmon stocks and fish health management, which is of less importance in New Zealand and Australia, where salmon are non-native.

6. New Zealand is the only country that does not have legislated aquaculture monitoring requirements and regulations on permitted environmental standards. Creation of aquaculture regulations is likely to remove inconsistencies in environmental standards and enable better enforcement of environmental standards.

7. Environmental impact in North America is primarily assessed by chemical measures e.g. free sulfides and redox potential, which have been validated as proxy measures of ecological benthic impact. The use of chemical measures provides a non-subjective assessment, reduces compliance costs and allows for greater spatial replication, which will improve far-field assessment and forecasting.

8. Countries are confronting the same environmental issues including organic waste production, disease, use of therapeutic agents and chemicals, escapes of aquaculture stock, bio-fouling management and sustainability of feed ingredients (OCAD, 2001).

Modelling studies that are verified by long-term environmental data sets are required to address the increasing concern about far-field and cumulative effects of aquaculture.

9. Voluntary BMP certification schemes (GAA, ASC) have higher environmental performance standards than those of national regulators.

In marine aquaculture, environmental quality, growth and health of fish, and farms profits are intimately linked. Thus, minimising the environmental impacts of marine aquaculture should be a common goal for regulatory authorities and producers. Improvements in the environmental management of aquaculture will produce both environmental and economic benefits. Comparison of the salmon farming operational practices in New Zealand with international best management practices using a case study of the New Zealand King Salmon Company has identified a number of areas where finfish aquaculture in New Zealand could potentially be improved (Table 9). Many of these suggested improvements require changes at the governmental level as well as changes by the producer. The lack of water space available for aquaculture and the restrictions of current resource consent conditions have limited the uptake of best management practices such as site rotation, fallowing and optimal net-pen arrangements. Based on overseas examples, implementation of these BMP will improve the economic and environmental performance of finfish aquaculture in New Zealand, facilitating the sustainable growth of New Zealand's aquaculture industry.

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8 Appendix

Table A. Hargrave's Decision Support System: far-field and near-field information used for assessing the potential impacts of a new aquaculture development (Hargrave, 2002).

	Far-field information required	Rational
1	Are there shellfish closures in the area? If so, what is the distance from the proposed site?	Shellfish closures would indicated poor quality water or the frequent presence of harmful algal blooms
2	Are there any macroalgae beds or is there any harvesting of fish or shellfish within 300 m from the proposed site?	Waste from farms may negatively affect growth of macroalgae. The farm may prevent the local community from accessing harvest areas.
3	Is there another finfish farm within 3 km?	Farms positioned too close to one another increase the disease transmission risks and cumulative load on the environment.
4	Is there a marine protected area (MPA) within 5 km?	Sufficient distance is required from MPA to minimise any potential adverse effects.
5	Do endangered species use the area within 5 km of the proposed site?	Sufficient distance is required from critical habitats to minimise any potential adverse effects.
6	Is there a river discharge in the area or seasonal water stratification?	Stratification is likely to reduce DO and increase the quantity of nutrients in deeper waters.
7	Is there a sill within the bay?	Sills will reduce water exchange.
8	Is there any industry likely to affect water quality within 5 km of the proposed site?	Industry discharge may adversely affect water quality.
9	How many people live within 1 km of the site?	Sewage and urban discharge may adversely affect water quality.
10	Is there a critical fish habitat (e.g. spawning ground) within 1 km of the site?	For the protection of wild stocks.
	Near-field information required (at proposed site)	
11	Area of inlet/bay that farm will be located within.	Required to estimate water exchange in bay.
12	Lowest water depth	Required to ensure sufficient clearance (>5m) between the bottom of the nets and the sea bed for good horizontal waste dispersal.
13	Tidal range	
14	Current velocity	Required to estimate water exchange in bay
15	Dissolved oxygen in summer/autumn	DO must be >6.4 mg l^{-1} to avoid stressing fish
16	Turbidity measurement (Secchi disc)	Turbid waters are less desirable for salmon culture
17	What is the % of silt/clay in the sediment?	Sites with high currents will have a low silt %.
18	What is the % organic matter in the sediment?	Sites with lower % organic matter are less enriched.
19	Free sulfide in sediment	Lower sulfide concentrations indicate less enrichment.
20	Redox potential in sediment	Oxygenated sediment has positive potentials.
21	Number of sediment sampling sites	The more the better
22	Period over which current measurements were taken	The longer the better

Table B. Approximate licence and monitoring costs for finfish farms in Norway, Scotland, Canada, USA, Australia and New Zealand. Note that information on many of these figures is not publicly available.

Country	Cost of new application (NZ$)	Licence costs (NZ$)	Annual lease cost (NZ$)	Annual monitoring costs (NZ$)	References
Norway	1,000,000[20]	1,700,000[21] (1,000,000 in Finmark)	0	?	(Asche & Bjørndal, 2011)
Scotland	5000 + 145,000 km^{-2} [22]	9300 yr^{-1}	30 t^{-1}	?	(Marine Harvest, 2012)
Canada (British Columbia (BC), New Brunswick (NB), Nova Scotia (NS))	BC: 360,000–600,000[20]; NS: 1600[22]	BC: 450–550; NB: 60 yr^{-1}; NS: 500 yr^{-1}	BC:47,000 km^{-2}; NS: 1500 km^{-2}; NB: 30,000 km^{-2}	?	(GSGislason & Associates, 2004; DAAF, 2011; Marine Harvest, 2012; Nova Scotia Fisheries and Aquaculture, 2013)
USA (Maine, (ME))	?	ME: 2500	ME: 30,500 km^{-2}	?	(Maine Department of Marine Resources, 2013b)
Australia (Tasmania (T), South Australia (SA))	SA:5000[22]	T:3500 yr^{-1}; SA: 3600 yr^{-1}	T: 2000; SA: 2400	2400–18,000	(Seafood Services Australia, 2009; DPIWE, 2013; PIRSA, 2013)
New Zealand	>1,000,000[23]	2000	0	25,000	(Ministry for Primary Industries, 2013; M. Gillard, NZKS, pers. comm.)

[20] Includes EIA costs
[21] Licence cost per 780 t of fish produced
[22] New licence and lease permit costs only
[23] The whole application was for nine proposed sites, which was estimated to cost >$10 million. This cost includes plan changes and resource consents for 8 sites and a resource consent for 1 site under the EPA. Four of the nine sites were approved by the EPA.

Table C. General description of the Enrichment Stages (ES) used by Cawthron Institute to assessed the environmental impact of salmon farms (from Keeley, 2012). Low flow environments have an average current speed of < 9.5 cm s^{-1} and high flow environments have an average current speeds of < 9.5 cm s^{-1}.

ES	General description	Flow	Environmental characteristics
1	Natural/pristine conditions	Low	Environmental variables comparable to unpolluted/un-enriched pristine reference site.
		High	As for low flow, but infauna richness and abundances are naturally higher (~2× low flow ES1) and % organic matter slightly lower.
2	Minor enrichment. Low-level enrichment. Can occur naturally or from other diffuse anthropogenic sources.	Low	Richness usually greater than for reference conditions. Zone of 'enhancement' – minor increase in abundance possible. Mainly compositional change. Sediment chemistry unaffected or with only very minor effects.
		High	As for low flow.
3	Moderate enrichment. Clearly enriched and impacted. Significant community change evident.	Low	Notable abundance increase, richness and diversity usually lower than reference site. Opportunistic species (i.e. capitellid worms) begin to dominate.
		High	As for low flow.
4	High enrichment. Transitional stage between moderate effects and peak infauna abundance. Major community change.	Low	Diversity further reduced, abundances usually quite high but clearly sub-peak. Opportunistic species dominate but other taxa may still persist. Major sediment chemistry changes (approaching hypoxia).
		High	As for low flow but abundance can be very high while richness and diversity are not necessarily reduced.
5	Very high enrichment. State of peak infauna abundance.	Low	Very high numbers of 1 or 2 opportunistic species (i.e. capitellid worms, nematodes). Richness very low. Major sediment chemistry changes (hypoxia, moderate oxygen stress). Bacterial mat (*Beggiatoa*-like) usually evident. Out-gassing on disturbance.
		High	Abundances of opportunistic species can be extreme (10 × low flow ES 5 densities). Diversity usually significantly reduced but moderate richness can be maintained. Sediment organic content usually slightly elevated. Bacterial mat formation and out-gassing possible.
6	Excessive enrichment. Transitional stage between peak abundance and azoic (devoid of any organisms).	Low	Richness and diversity very low. Abundances of opportunistic species severely reduced from peak. But not azoic. Total abundance low but can be comparable to reference site. % organic matter can be very high (3–6 × reference levels).
		High	Opportunistic species strongly dominant, taxa richness and diversity substantially reduced. Total infauna abundance less than at sites further away from farm. Elevated organic matter and sulfide levels. Formation of bacterial mats and out-gassing.
7	Severe enrichment. Anoxic and azoic; sediments no longer capable of supporting infauna with organics accumulating.	Low	None, or only trace number of infauna remain. Some samples with no taxa. Spontaneous out-gassing. Bacterial mats usually present but can be suppressed. % organic matter can be very high (3–6 × reference levels).
		High	Not previously observed but assumed similar to low flow sites.