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Second Interim Report of the Working Group on Aquaculture (WGAQUA)

31 March – 4 April 2014

Vigo, Spain



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Executive summary

The WGAQUA held its second meeting from 31 March to 4 April 2014 in Vigo, Spain. It was hosted by Pepe Iglesias of the Instituto Espanol de Oceanografia, Centro Oceanografico de Vigo and was attended by 27 participants from 10 ICES countries (Annex 1). Progress on the ToRs, outreach/PR activities, cooperation with other WG and with advisory structures as well as science highlights are reported.

WGAQUA received an advice request from OSPAR (4/2014) on “Interactions between wild and captive fish stocks”. WGAQUA contributed information on the pressures to wild fish from several mariculture activities (introduction of antibiotics and other pharmaceuticals; parasite interactions; non-genetic interactions from mass releases of cultured organisms including fish escapes and bivalve transfers/spawning; release of nutrients and organic matter; addition of structure/habitat by bivalve culture, and utilization of trophic resources by mariculture). A detailed report was prepared for ACOM that included an update on the available knowledge on these aquaculture pressures and some examples of management solutions to mitigate these pressures on the marine environment. Aquaculture activities in the ICES and OSPAR regions are highly diverse and impacts on wild fish may be expected to be highly site-specific. Consequently, it was not possible for WGAQUA to reach generic conclusions on aquaculture interactions with wild fish, or to identify and prioritize major mariculture pressures that are applicable across the full ICES or OSPAR regions.

WGAQUA has accepted the invitation to participate in the work and deliberation of ISO TC 234 as a liaison organization (Level B). The draft standards on sea lice monitoring (document ISO/DIS 16541) were reviewed by WGAQUA and comments were relayed to ISO.

All twelve ToRs were discussed at the beginning of the meeting and it was decided to not to work on ToR a) and ToR b) this year, but finalise those in the last year. For ToRs d)-l) ToR leaders prepared an outline of publication intersessionally and presented that at meeting. Several ToRs showed considerable overlap. Based on attendance and expertise subgroups were formed to work on overlapping ToRs. ToR d – l were grouped according to overlap and three sub-groups were formed to work on them. The chosen structure fits well with the themes determined during the first WGAQUA meeting in 2013: Benthic Effects Theme, Pest Management Theme and Ecosystem Interactions Theme. Work will continue intersessionally.

Emerging aquaculture issues (ToR c) were highlighted. It was observed that the present expertise of WGAQUA does not cover all topics that were identified. It should be noted that WGAQUA covers a wide range of subjects. Compared to EGs dealing with fish issues there is much less specialisation. Aquaculture production takes up 40% of the global seafood production. However, this is not reflected in the number EGs working on aquaculture topics.

1 Administrative details

Working Group name

Aquaculture

Year of Appointment

2014

Reporting year within current cycle (1, 2 or 3)

2

Chair(s)

Karin Boxaspen, Norway

Peter Cranford, Canada

Pauline Kamermans, The Netherlands

Meeting venue

Vigo, Spain

Meeting dates

31 March – 4 April 2014

2 Terms of Reference a) – l)

ToR a) Synthesise reports and recommendations by WGAGFM, WGPDMO, WGH-ABD, and WGECO on the environmental dependence and effects of aquaculture (not worked on in 2014)

ToR b) Synthesise previous science advice provided by ICES SGs and WGs related to sustainable aquaculture (not worked on in 2014)

ToR c) Identify emerging aquaculture issues and related science advisory needs for maintaining the sustainability of living marine resources and the protection of the marine environment. The task is to highlight new and important issues that may require additional attention by the WGAQUA and/or another Expert Group as opposed to providing a comprehensive analysis (group exercise)

ToR d) Identify and assess approaches for analysing the effects of aquaculture on benthic habitats with a focus on rocky and mixed substrata bottoms. Recommend approaches to assess/monitor these habitats (Raymond Bannister)

ToR e) Identify and assess approaches for analysing the interactions between aquaculture and eelgrass and maerl beds. Recommend approaches to assess/monitor these habitats (Pauline Kamermans)

ToR f) Analyse and assess the environmental effects of biofouling pest management in aquaculture with an emphasis on i) chemical release, ii) benthic organic enrichment, iii) waste management, and iv) propagule pressure. Ultimately, a risk assessment framework will be developed with respect to treatments for bivalve aquaculture pests within a greater pest management framework (Thomas Landry)

- ToR g) Analyse and assess the environmental effects of sea lice pest management in aquaculture with an emphasis on i) therapeutant release, ii) waste management, and iii) propagule pressure (Dave Jackson)
- ToR h) Assess and analyse issues relating to the attraction and repulsion of wild populations by fish and shellfish farms and of the impact of this on these populations and the individuals (Chris McKindsey)
- ToR i) Analyse and assess the potential ecosystem services and impacts of aquaculture, including extractive aquaculture approaches for environmental impact biomitigation (Myriam Callier)
- ToR j) Assess the knowledge base on acceptance of aquaculture in Marine Protected Areas (Adele Boyd)
- ToR k) Characterize risks, real and perceived, and potential ecological benefits associated with introducing foreign strains and species of finfish and shellfish and other invertebrates for aquaculture purposes (Gef Flimlin)
- ToR l) OSPAR 4/2014 Request Interactions between wild and captive fish stocks (Peter Cranford)

3 Summary of Work plan

Year 2	ToR leaders prepared an outline of each ToR report (potential publication) intersessionally and presented that at the meeting. WGAQUA members worked on ToRs c-l during the meeting. Outreach/PR activities were evaluated and an outreach plan for Year 3 was developed.
Year 3	ToR leaders prepare outline of publication intersessionally and present that at meeting. During meeting finalise products depending on attendance (number of people and their expertise). Discuss future of group.

4 List of Outcomes and Achievements of the WG in this delivery period

- The WGAQUA response to the OSPAR request (4/2014) was finalised (see Annex 3) through the preparation of a report that included a synthesis of science knowledge on a large number of potential aquaculture pressures on wild fish across a broad geographic area. This was a major undertaking by a large number of working group members and required considerable inter-sessional discussion and work. It was a true team effort that demonstrated the capacity of WGAQUA to deliver on complex science advice requests.
- The ICES application for liaison A status to ISO/TC 234 was accepted and the WGAQUA science advice chair has taken a coordinating role within ICES for reviewing the progress of ISO aquaculture standards development. Several draft standards were presented to WGAQUA for review and written comments were relayed to the ICES secretariat prior to voting and to the appropriate ISO drafting committee.
- Benthic Effects. An outline for a publication on *Assessing and developing tools for monitoring changes in marine benthic habitats associated with aquaculture in the North Atlantic area* was agreed on and relevant information on the topic was collected.

Work on the publication will continue intersessionally. ToR j *Acceptance of aquaculture in Marine Protected Areas* was discussed and reformulated.

- **Pest management.** In aquaculture, sea lice on salmon farms is the pest that has received the most attention. More recently, tunicate infestation on mussel farms is another pest causing significant problems. The management of these two pest situations presents an opportunity to assess the option of considering an integrated approach to the Management of Pests in Aquaculture. A pest is defined as “any organism that damages crops, injures or irritates livestock or man, or reduces the fertility of land”. FAO (2013) defines Integrated Pest Management (IPM) as “the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to ecosystems and encourages natural pest control mechanisms”. In addressing this specific topic WGAQUA has developed a work programme for 2014/2015 covering the following: *Broad criteria for treatment use; Areas for further work (mechanical treatment, skirts, etc); Need for an expert group and appropriate ToRs; Assessment of long term/large scale environmental impacts of various treatments balanced by economics; Vaccines.*
- **Ecosystem Interactions.** Work was done on ToR h. *Attraction and repulsion of wild populations by fish and shellfish farms* and ToR i. *Potential ecosystem services and impacts of aquaculture* in the context of the OSPAR request (4/2014). Work on publications will continue intersessionally.
- **Emerging aquaculture issues** were highlighted (see 5 below). It was observed that the present expertise of WGAQUA does not cover all topics that were identified. E.g. we lack expertise on Product quality, Consumer Safety & Health, Aquatic Animal Health & Welfare. It should be noted that WGAQUA covers a wide range of subjects. Compared to EGs dealing with fish issues there is much less specialisation. Only WGAGFM (genetics), WGPDMO (disease), SGSA (socio-economics) deal with specific aspects of aquaculture. Aquaculture production takes up 40% of the global seafood production. However, this is not reflected in the number EGs working on aquaculture topics.

5 Progress report on ToRs and workplan

- Given the large number of ToRs to work on and the OSPAR request that needed to be finished soon after the meeting it was decided not to work on ToR a) and ToR b) this year. Most work was done in 2013 (see last year's report). In Year 3 the Annual reports prepared since 2013 by several ICES expert groups (SGSA, WGAGFM, WGEIM, WGICZM, WGITMO, WGMASC, WGPDMO, WGHABD, WGEKO) will be examined to address ToR a and ToR b at the same time.
- The purpose of ToR c) is to highlight new and important issues that may require additional attention by the WGAQUA and/or another Expert Group as opposed to providing a comprehensive analysis. The list that was prepared last year (see

Annex 4) was revisited. Apart from scientists, we have a fairly good representation of managers in our group. Unfortunately, the EATiP representative that was invited to our meeting was unable to attend. Thus, input from industry was limited, but having an extension officer among us was very helpful.

The following topics were highlighted as important:

- Integration with the Environment is important as shown by the OSPAR request
 - Landbased / offshore production (space constraints, technology restrictions, process focussed scale, salt water on land)
 - IMTA (juvenile supply, new species, nutrient trading, upwelling, ecological aquaculture)
 - Mass production of micro- and macro-algae
 - Product quality standards
 - Optimising production (sterile, life cycle (GMO for WGAGFM))
 - Sustainable feed production (feed conversion, anti-nutritive, animal by-products as feed)
 - Adaptation to climate change to maintain aquaculture production
 - Knowledge management (LCA, GIS spatial planning, access to open data, implementation of knowledge data management)
 - Health and welfare (consumer perspective, EU legislation, cleaner fish, how to measure welfare)
- ToR leaders prepared an outline of publication intersessionally and presented that at meeting. ToR d – l were grouped according to overlap and three sub-groups were formed to work on them (see Table x). Work will continue intersessionally. During the meeting in Year 3 the products will be finalised.
- Outreach/PR activities
 - The websites of Ifremer and IMARES presented a report on the meeting in Palavas.
 - An article was published in the Faro de Vigo on our meeting in Vigo.
 - Plan for year 3: think about a workshop for stakeholders after the WGAQUA meeting; send ICES publications to key people; discuss role of WGAQUA within ICES with Adi Kellerman and Ole Torrissen
- Cooperation with other WG
 - Peter Cranford joined part of the SGSA meeting in Biddiford, Maine and presented an overview of WGAQUA science and advisory activities. To promote further cooperation between aquaculture expert groups in the future, the SGSA was invited to meet concurrently with WGAQUA in Rhode Island in 2015.
- Cooperation with Advisory structures
 - WGAQUA worked on an OSPAR request for ACOM and provided advice on ISO standards.
- Science Highlights
 - A theme session on “The application of science for ecosystem-based management of aquaculture” will be held at the 2014 Annual Science

Conference. Conveners are Dave Jackson, Heather Moore and Neil Auchterlonie.

- Two publications that were prepared during meetings of the WGMASC came out: Muehlbauer F., D. Fraser, M. Brenner, K. Van Nieuwenhove, B.H. Buck, O. Strand, J. Mazurié, G. Thorarinsdottir, P. Dolmer, F. O'Beirn, A. Sanchez-Mata, G. Flimlin, P. Kamermans (2014). Bivalve aquaculture transfers in Atlantic Europe. Part A: Transfer activities and legal framework. *Ocean & Coastal Management* 89: 127–138. ; Benner M., D. Fraser, K. Van Nieuwenhove, F. O'Beirn, B.H. Buck, J. Mazurié, G. Thorarinsdottir, P. Dolmer, A. Sanchez-Mata, O. Strand, G. Flimlin, L. Miossec, P. Kamermans (2014). Bivalve aquaculture transfers in Atlantic Europe. Part B: Environmental impacts of transfer activities. *Ocean & Coastal Management* 89: 139–146.

6 Revisions to the work plan and justification

Several ToRs showed considerable overlap. Based on attendance and expertise subgroups were formed to work on overlapping ToRs (Table 1). In some cases it was decided to merge ToRs. E.g. ToR d) and ToR e) were merged into “Assessing and developing tools for monitoring changes in marine benthic habitats associated with aquaculture in the North Atlantic area”. The ToRs of subgroup II were all placed under the umbrella of pest management. And in subgroup III ToR h) and ToR i) fed into the OSPAR request of ToR l). The chosen structure fits well with the themes (and theme leaders) determined during the first WGAQUA meeting in 2013: Benthic Effects Theme led by Raymond Bannister (Norway), Pest Management Theme led by Dave Jackson (Ireland), Ecosystem Interactions Theme led by Chris McKindsey (Canada). ToR j) was discussed extensively which led to a change in focus as presented in the recommendations (#4 in Annex 2).

Table 1. Distribution of WGAQUA participants among ToR clusters.

ToRs	Cluster	Leader	Participants
d. Effects of aquaculture on benthic habitats with a focus on rocky and mixed substrata bottoms	I	Raymond Bannister	Corina Busby Francis O'Beirn Else Marie Djupevag Manuel Garcia Tasende
e. Interactions between aquaculture and eelgrass and maerl beds	I	Pauline Kamermans	
j. Acceptance of aquaculture in Marine Protected Areas	I	Adele Boyd	
f. Environmental effects of biofouling pest management in aquaculture	II	Thomas Landry	Karin Boxaspen Knud Simonsen Camino Gestal Henrik Hareide Olav Moberg
g. Environmental effects of sea lice pest management in aquaculture	II	Dave Jackson	
k. Introducing foreign strains and species of finfish and shellfish and other invertebrates for aquaculture purposes	II	Gef Flimlin	
l. Special request: Interactions between wild and captive fish	III	Peter Cranford	David Bengtson

stocks (OSPAR 4/2014)			Ulfert Focken
h. Attraction and repulsion of wild populations by fish and shellfish farms	III	Chris McKindsey	Jose Iglesias Heather Moore Terje Svasand
i. Potential ecosystem services and impacts of aquaculture	III	Myriam Callier	Carmen Gonzalez Ulrich Knaus Oivind Strand Stephen Cross Knud Simonsen

7 Next meetings

The next meeting will be held in the USA (Rhode Island), 16–20 March 2015.

Annex 1: List of participants

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Annex 2: Recommendations

Recommendation	Adressed to
1. Member states (Norway in particular, 2011) have asked if ICES can give advice related to the sustainability of aquaculture (finfish in particular). WGAQUA was formed, in part, to facilitate the provision of science advice on aquaculture issues and to attract a broad mix of finfish, shellfish and macroalgal aquaculture scientists. The membership of WGAQUA currently stands at 55 scientists from 15 ICES member states. A Science Advice co-chair has been tasked specifically with coordinating group responses to formal advisory requests. WGAQUA recommends that ACOM initiate the process of drafting specific advice questions for presentation to WGAQUA members at the 2014 annual meeting. The Science Advice chair is available to participate as required in developing these questions and for ensuring a timely response by WGAQUA to each query.	ACOM
2. The WGAQUA has been promoting our role in providing advice to clients on a wide range of aquaculture issues. OSPAR advice request 24/2014 targeted an extremely wide-ranging topic that is applicable to a broad range of mariculture activities in a multitude of environmental settings that includes most ICES member countries. Such a large generic advisory request greatly diluted the capacity of WGAQUA to provide advice in a form that can be easily interpreted and utilized by clients. It is therefore recommended that ICES communicate with OSPAR and other clients the need to focus future questions on individual aquaculture pressures (e.g. sea lice, escapes, organic wastes, etc.) for specific mariculture species, and for particular regional seas.	ACOM, SCICOM
3. WGAQUA recommends that ICES contact delegates to seek additional representation on WGAQUA for experts on macroalgae aquaculture as well as to seek members from ICES states that are currently not represented in the group.	SCICOM, Delegates
4. WGAQUA recommends that the focus of ToR j be changed to <i>The management of aquaculture within Natura 2000 designated areas</i> . The designation of maine sites for the protection/conservation of species and habitats can cause restrictions for fish and shellfish-farmers and conflicts between aquaculture producers and environmental authorities. Whilst spatial planning can help with these issues, this is rarely a joint process involving all stakeholders. Furthermore, the benefits of aquaculture to marine designated sites (i.e ecosystem services) are often not communicated. European Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, and Directive 2009/147/EC on the Conservation of wild birds (referred to as the Habitats and Birds Directives respectively) were developed with the aims of protecting habitats and species considered to be of European interest. This is achieved through member states designating sites of Special areas of Conservation (SAC) for the protection of habitats (as listed in Annex I of the habitats directive) and species (as listed in Annex II of the habitats directive) and Special Protection Areas (SPA) for the protection wild birds and the habitats of listed species. SAC and SPA designated sites form the Natura 2000 network of sites. The WGAQUA will review designations such as Natura 2000, and compare the implementation in different ICES countries and identify different management strategies. In addition the knowledge of the potential impacts of shellfish aquaculture (both	SCICOM

positive and negative) in different countries will be evaluated. WGAQUA can provide science-based recommendations on such topics as criteria and thresholds for management decisions, an evaluation of present management regimes, and how to deal with the lack of baseline information.

Annex 3: OSPAR science advice request (2013/4)

Science Advisory Report: **Interactions Between Wild and Captive Fish Stocks.**

Client: **OSPAR**

Draft Date: **7 May 2014**

1. **OSPAR science advise request (2013/4)**

ICES ACOM requested WGAQUA to provide science advice for OSPAR related to “interactions between wild and captive fish stocks” (received by WGAQUA on 13 August, 2013):

- a) Recalling the conclusion of the QSR 2010 that mariculture is a growing activity in the OSPAR maritime area, EIHA 2012 considered the potential for increasing environmental pressure relating to the growth of this industry. As yet this is not an established work stream within EIHA, and Contracting Parties have requested that more information be brought forwards on this issue. This was reiterated by EIHA 2013.
- b) Mariculture has a number of associated environmental pressures such as the introduction of non-indigenous species, which can have ecological and genetic impacts on marine environment and especially on wild fish stocks; in addition, pressures from mariculture might include:
 - i. introduction of antibiotics and other pharmaceuticals;
 - ii. transfer of disease and parasite interactions;
 - iii. release of nutrients and organic matters;
 - iv. introgression of foreign genes, from both hatchery-reared fish and genetically modified fish and invertebrates, in wild populations;
 - v. effects on small cetaceans, such as the bottlenose dolphin, due to their interaction with aquaculture cages
- c) EIHA proposes that OSPAR requests ICES to provide:
 - i. an update on the available knowledge on these issues;
 - ii. concrete examples of management solutions to mitigate these pressures on the marine environment;
 - iii. advice on which pressures have sufficient documentation regarding their impacts to implement relevant monitoring and suggest a way forward to manage these pressures.
- d) It may be appropriate to explore cooperation with other competent authorities working in this field, such as the European Food Safety Authority with respect to disease transfer or parasites, or the North Atlantic Salmon Conservation Organisation (NASCO), in particular with respect to existing cooperation between NASCO and ICES on issues pertaining to pressures from mariculture.

2. Scope of WGAQUA responsibilities

Discussions with ACOM on how the OSPAR request will be addressed by various ICES expert groups resulted in WGAQUA contributing information on the following environmental pressures from mariculture activities:

- 1) introduction of antibiotics and other pharmaceuticals;
- 2) parasite interactions;
- 3) non-genetic interactions from mass releases of cultured organisms (fish escapes and bivalve transfers/spawning);
- 4) release of nutrients and organic matter;
- 5) addition of structure/habitat by bivalve culture, and
- 6) utilization of trophic resources by mariculture.

This list includes three topics not specifically identified by OSPAR (items 3, 5 and 6). These topics were deemed necessary for a thorough assessment of mariculture interactions with wild fish. The remaining pressures identified by OSPAR are to be addressed separately by the Working Group on Application of Genetics in Fisheries and Mariculture (WGAGFM; introgression of foreign genes in wild populations), the Working Group on Pathology and Diseases of Marine Organisms (WGPDMO; transfer of disease) and the Working Group on Marine Mammal Ecology (WGMME; effects on small cetaceans). Each working group was tasked to deliver their separate advisory report to an Advice Drafting Group (ADG) prior to a meeting planned for 18-20 June, 2014.

The WGAQUA was established by ICES in 2013 with the mandate of improving the sustainability of aquaculture in the ICES area through the provision of state of the art science and advice. Our vision is “a diverse aquaculture sector that will meet the increasing demand for seafood and products while providing jobs, products, and services in harmony with healthy, productive, and resilient freshwater and marine ecosystems.” Achieving this vision requires that aquaculture decision making and marine management include as nested components; 1) a knowledge-based approach, 2) an ecosystem-based approach, and 3) an integrative management framework that includes economic, environmental, social and equity considerations. Consequently, WGAQUA promoted the inclusion of stakeholder involvement in group discussions related to this request, including participation in the annual WGAQUA meeting in Vigo, Spain (31 March to 4 April, 2014). The North Atlantic Salmon Conservation Organisation (NASCO) declined our invitation to participate. The European Aquaculture Technology and Innovation Platform (EATiP), which promotes technology and innovation in aquaculture, requested participation, but was unable to attend the Vigo meeting.

Initial discussions within WGAQUA on the overall scope of this request for advice were held via e-mail and several guiding principles were set as a basis for preparing this document:

- 1) The terms “mariculture” and “wild fish stocks” are both considered to be inclusive of marine and anadromous finfish as well as marine and brackish-water shellfish.
- 2) Wild fish interactions with mariculture can occur within the cultured species native habitat as well as when introduced to new areas. Consequently, the mariculture of native and non- indigenous species was included in our analysis.

- 3) Interactions between wild and cultured species may be positive, negative or neutral. The WGAQUA attempted to evaluate all outcomes and provide a balanced assessment.
- 4) Interactions between cultured and wild species may occur as a result of direct interactions and/or indirect effects on habitat, trophic resources, competition, predation, etc.

The science advice presented in this report builds upon the content of many previous ICES reports and publications, including:

- a) 2010 ICES advice to OSPAR: *Effect of mariculture on wild fish (OSPAR 2010/3)*.

Summary: "In the OSPAR area, the degree of interactions may be moderate between finfish mariculture and wild fish populations at the scale of a river local to a salmon farm, but are lower at a broader scale. The supply of food for mariculture creates a demand for small pelagic fish. ICES has advised that the fishing mortality on some small pelagic stocks should be reduced."

- b) Working Group on Marine Shellfish Culture (WGMASC) publications:

- Cranford P.J., Kamermans P., Krause G., Mazurié J., Buck B., Dolmer P., Fraser D., Gubbins M., Van Nieuwenhove K., O'Beirn F.X., Sanchez-Mata A., Thorarinsdóttir G.G., Strand Ø. 2012. *An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts*. Aquaculture Environmental Interactions 2: 193-213.

This paper summarizes ecological interactions with bivalve aquaculture and the attributes of available integrative management frameworks, discusses the potential management roles of ecological modelling and indicator-based approaches for describing ecosystem status and aquaculture impacts. A bivalve aquaculture management framework is recommended including the identification of performance indicators related to specific environmental effects from bivalve culture operations.

- Brenner M., D. Fraser, K. Van Nieuwenhove, F. O'Beirn, B. H. Buck, J. Mazurié, G. Thorarinsdóttir, P. Dolmer, A. Sanchez-Mata, O. Strand, G. Flimlin, P. Kamermans. 2014. *Bivalve aquaculture transfers in Atlantic Europe. Part B: environmental impacts of transfer activities*. Ocean and Coastal Management 89: 139-146.

This paper provides a list of threats related to bivalve transfer activities, describes the impacts along the European Atlantic coast, and identifies hitch hiker species, fouling organisms or infectious agents which can be translocated with a target species. Further, the study highlights the need for thorough, standard risk reduction measures designed to minimise the impact on ecosystems worldwide.

- c) Working Group on Environmental Interactions of Mariculture (WGEIM) annual reports and publications have provided relevant advice and recommendations on the following topics:

- interbreeding of wild and escaped fish,
- environmental effects of the sea lice therapeutants,
- potential impact of escaped non-salmonid aquaculture candidates on local stocks,
- alternative sources of lipid and protein to fish oil and fish meal for aquafeed,
- sustainability indices for mariculture operations,
- ecological risks, uncertainties and management of coastal aquaculture,
- sustainable development and technological change in mariculture, and
- offshore farming.

3. Mariculture status in ICES member countries and pressures on wild species

Aquaculture has been responsible for the continuing growth in global fish production since capture production levelled off in the mid-1990s (FAO, 2012). Aquaculture contributions to total world fish production climbed steadily from 20.9 percent in 1995 to 40.3 percent in 2010. Mariculture operations in ICES member countries produced a total of 2.3 million tonnes of fish and bivalve molluscs in 2012. Other mariculture species contributed only a small fraction of this production and are therefore excluded from further discussion. Norway contributed 57% of all production in the ICES region, with the vast majority coming from the culture of diadromous fish (Figure 1). Spain was the second largest producer, but with 84% of production coming from bivalve molluscs. The UK, France and the USA were also among the top-5 producers in the ICES region (Figure 1), with the UK producing mainly fish (86%) and the USA and France primarily producing molluscs (> 86%). While global aquaculture production continues to increase in many parts of the world, it has recently ceased to expand in both North America and Europe (FAO, 2012).

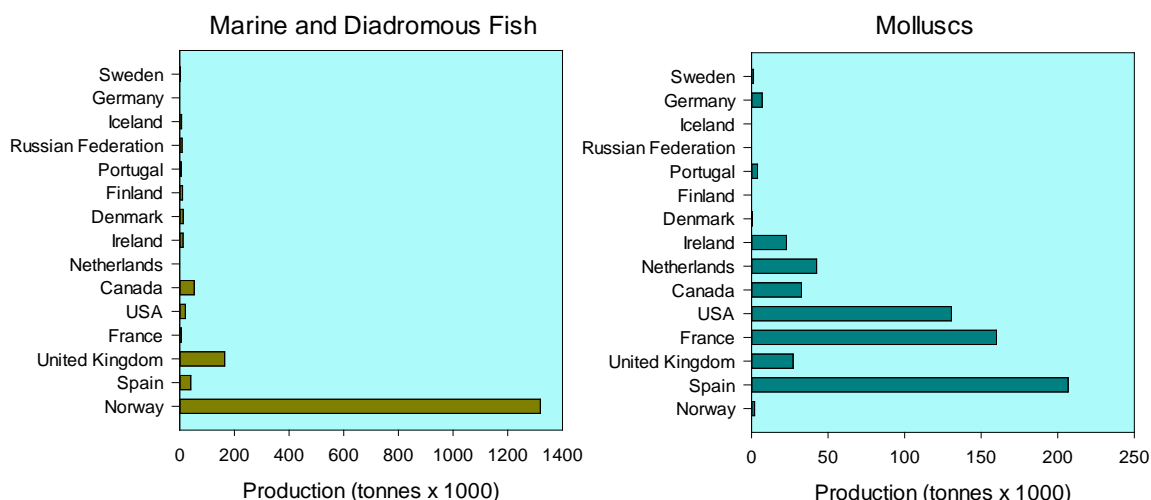


Figure 1. Aquaculture production of marine and brackish water fish and molluscs by ICES member countries in 2012 (statistics from the on-line FAO database). Countries are listed in order of total production. Note that this analysis neglected to include the Faroe Islands, which produced 72 000 tonnes of Atlantic salmon in 2012; making it the 7th largest aquaculture producer in the ICES region.

Mariculture places numerous pressures (both positive and negative) on ecosystem components that may affect wild fish stocks (Table 1; Figures 2 and 3). Pressures on wild fish from the culture of carnivorous fish species are related primarily to; (1) chemical use, including; pesticides, antibiotics, antifoulants and disinfectants, (2) effects on natural habitats, (3) genetic contamination and competition for limited resources between escaped farmed and native stocks, (4) possible introduction of non-native species, (5) spread of disease and parasites among native fish populations, (6) discharges of particulate organic and dissolved nutrient wastes, (7) attraction and entanglement of marine mammals in nets, and (8) the use of wild fish as a source of food for farmed fish (Table 1; Figure 2). Dense bivalve populations exert numerous pressures on the environment (e.g. Dame 1998; Souchu *et al.* 2001; Christensen *et al.* 2003; Newell 2004; Cranford *et al.* 2006 and 2007; Dumbauld *et al.* 2009; Forrest *et al.* 2009; McKindsey *et al.* 2011; Shumway 2011) that may have implications for wild species. Environmental issues are related primarily to how intensive bivalve culture interacts with, and potentially controls, fundamental ecosystem processes (energy flow and nutrient cycling) at the coastal ecosystem scale (Table 1). Where negative environmental effects have been reported, they are generally linked to the consumption of suspended particles and particularly the phytoplankton, effects on coastal nutrient dynamics from ammonia excretion and organic waste recycling, and effects resulting from the translocation of suspended matter from pelagic to benthic compartments (Figure 3). The large reproductive output from farmed bivalves, the unintentional transport and introduction of invasive species, and the spread of diseases from hatcheries and spat collection areas may also have implications for native populations. Positive effects on biodiversity and productivity can result from the introduction of biotic and abiotic structures to the system, the increase or alteration of prey availability (cultured and fouling species), the capacity of bivalve filter-feeders to clarify water, and/or the enhancement of seabed organic enrichment (D'Amours *et al.* 2008; Callier *et al.* 2008).

Given the intensity of mariculture activities in some ICES member countries, the numerous pressures these activities may exert at the farm- to ecosystem scale, and the

complexity of environment interactions, an ecosystem-based perspective was considered essential for assessing potential effects on wild fish. To ensure that human activities in the marine environment are carried out in a sustainable manner, numerous international maritime policies have been implemented in ICES member countries, including the European Union *Water Framework* and *Marine Strategy Directives*, the Canadian *Oceans Act*, and the United States *Ocean Action Plan*. These legislations all promote an ecosystem approach to resource management that considers the best available scientific knowledge about the ecosystem and its dynamics, as well as the social and economic benefits that can be derived from resource utilization. An ecosystem approach to aquaculture was defined by the FAO (2010) as “a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems.” In addition to addressing direct effects of mariculture on native fish, the WGAQUA attempted to incorporate available knowledge on mariculture-induced changes in ecosystem structure (biotic and abiotic) and function (e.g. energy flow, nutrient cycling, competition and predator-prey relationships). This approach was taken to consider the effects of any changes in natural bottom-up and top-down controls on the survival, distribution and productivity of wild fish.

Table 1. Potential pressures on wild fish from mariculture activities and ICES expert group advisory responsibilities.

Mariculture species	Pressure on wild fish	ICES EG
Bivalve molluscs (e.g. mussels, oysters, clams, cockles)	habitat formation (suspended structures)	WGAQUA
	organic wastes (faeces and pseudofaeces)	WGAQUA
	nutrient addition (excretion) and removal (harvest)	WGAQUA
	antifouling treatments	WGAQUA
	disease spread	WGPDMO
	introduction of non-resident species	WGAQUA
	unintended spread of hitch-hiker species	WGAQUA
	competition for seston/phytoplankton	WGAQUA
	control of phytoplankton (biomass, size)	WGAQUA
	predation on planktonic life-stages	WGAQUA
	ecological services	WGAQUA
Carnivorous fish (e.g. salmon, trout, seabream, seabass, cod, halibut)	Chemicals (pesticides, medications, antifoulants, disinfectants)	WGAQUA
	organic wastes (faeces)	WGAQUA
	nutrient wastes (excretion)	WGAQUA
	escapes (competition/predation)	WGAQUA
	escapes (genetic impacts)	WGAGFM
	disease (spread of infectious agents)	WGPDMO
	parasites (sea lice)	WGAQUA
	reliance on wild fisheries for feed	WGAQUA
	structure interactions - mammals	WGMME
	structure interactions – habitat formation	WGAQUA

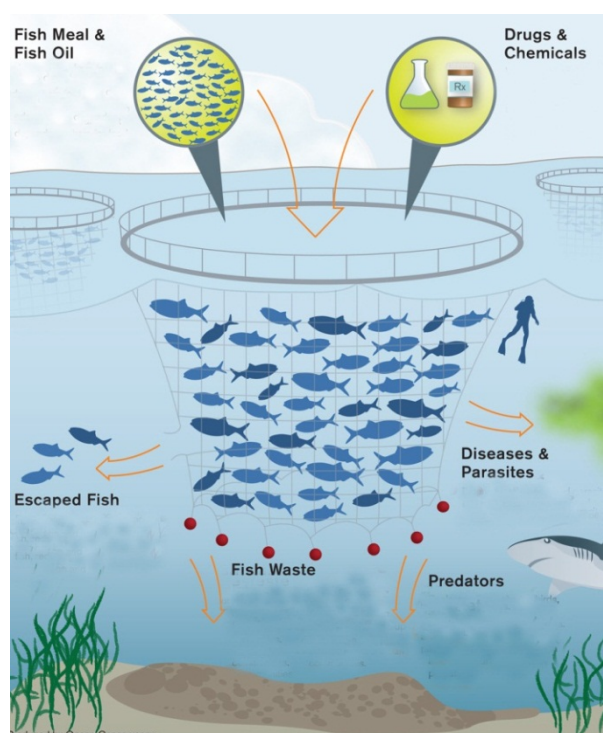


Figure 2. Diagram of open-water carnivorous fish aquaculture and major pressures on coastal ecosystems and wild fish (modified from original produced by Ocean Conservancy).

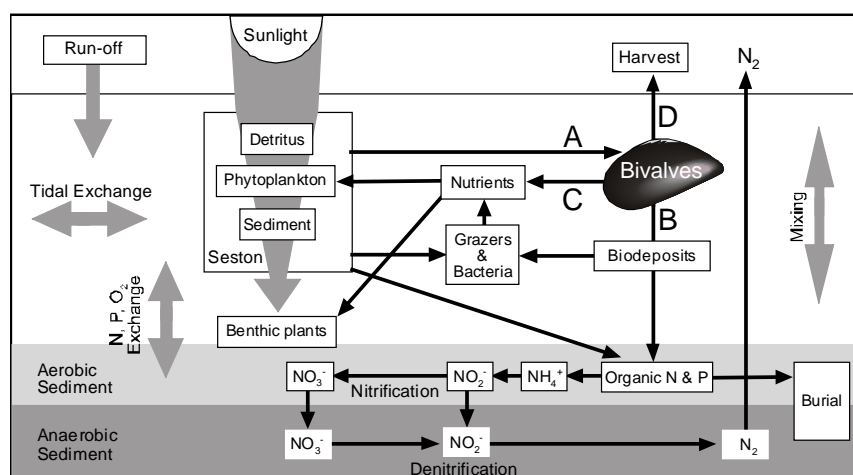


Figure 3. Conceptual diagram of bivalve aquaculture interactions in coastal ecosystems related to: (A) the removal of suspended particulate matter (seston) during filter feeding; (B) the biodeposition of undigested organic matter in feces and pseudofeces; (C) the excretion of ammonia nitrogen; and (D) the removal of materials (nutrients) in the bivalve harvest (Cranford *et al.* 2006).

References

- FAO, 2010. Aquaculture development. 4. Ecosystem approach to aquaculture. FAO Technical Guidelines for Responsible Fisheries. No. 5, Suppl. 4. Rome. 53 pp.
- FAO, 2012. The state of world fisheries and aquaculture 2012. Rome. 209 pp.

4. Knowledge on mariculture interactions with wild fish

The objective of preparing the following state of knowledge was not to provide an exhaustive literature review on the effects of mariculture pressures on the state of fish stocks and any ensuing impacts on environmental services, but rather to summarize the key findings, to identify priority issues and to characterize degrees of confidence and uncertainties in the conclusions.

4.1 Wild fish interactions with mass releases of cultured organisms

4.1.1 Movement of shellfish (Heather Moore, UK; Gef Flimlin, USA; Camino Gestal, Spain)

There is a long history of the movement of shellfish around the world (Wolff and Reise 2002). The objective of relaying shellfish from their area of origin for grow-out or sale is always economic, to develop a sustainable food supply, to replenish a depleted stock, or to start a new culture. This is in contrast to the inadvertent anthropogenic spreading of species via e.g. ballast waters and hull fouling. ICES Member Countries import live organisms from 32 countries and molluscs are among the most important taxa transported (WGITMO 2006). There are inherent risks associated with transfer of shellfish including introduction of non-indigenous species (NIS), potentially toxic algae, diseases, pests, bacteria, viruses or parasites associated with the translocated species. In addition there are potential implications from interactions with wild and cultured stocks, including impacts on; genetic integrity and biodiversity of local stocks, recruitment, sterilization, reduced fitness and fecundity, meat content, competition and predation, diversity, and physiological and morphological traits (Ambariyanto and Seed 1991, Calvo-Ugarteburu and McQuaid 1998, Camacho *et al.* 1997, Desclaux *et al.* 2004, Dethlefsen 1975, Taskinen 1998, Wegeberg and Jensen 1999, Wegeberg and Jensen 2003, Brenner *et al.* 2014). Many examples of severe ecological impacts have been documented worldwide owing to the intentional or unintentional translocation of animals (The Working Group on Introductions and Transfers of Marine Organisms (WGITMO) reports and The Study Group on Ballast and Other Ship Vectors (SGBOSV)).

Bivalve movements by humans for the purpose of aquaculture can be categorized into *transfers* and *introductions* (Beaumont 2000). A *transfer* is the intentional movement of individuals from one area to another within the natural range of the species (this would include the restocking of a habitat once known to have been occupied by a particular species or establishing aquaculture farms in areas that have had natural stocks in the past which are no longer productive for that species). In contrast, the movement of individuals to another geographical region where that species has never been present before is referred to as an *introduction*. This process can include the intentional introduction of non-indigenous species, e.g. the Pacific oyster (*Crassostrea gigas*) into the Pacific Northwest of the US and Europe.

The WGMASC discussed shellfish transfers under seven headings and these have been summarised in Table 2. The introduction of NIS into a new area presents several major challenges. The first is the ecological, environmental and economic impacts of introduced species, especially those which could become established in the receiving environment if they escape the confines of cultivation. Such new populations may have adverse impacts on native species and ecosystems but the scope of these potential impacts may or may not be significant. The second challenge concerns the potential significant genetic impacts of introduced species, relative to their mixing with

farmed and wild stocks, and the release of genetically modified organisms. The third challenge concerns the inadvertent movement of organisms associated with the target (host) species; this includes both pathogens and other organisms that are transferred with the target species. The mass transfer of animals and plants without inspection, quarantine, or other management procedures, has inevitably led to the simultaneous introduction of pathogenic or parasitic agents, causing harm to the development and growth of new fishery resources and to native fisheries (WGITMO 2011). A variety of rules and restrictions apply to shellfish movements, however the proposal for mandatory monitoring and scoring of NIS to look at “trend indicators for NIS” (Dutch Government, January 2013, Gittenberg pers.comm.) would provide a better understanding of their impact on marine biodiversity.

Transfer of bivalves from one area to another within the natural range of the species has a number of potential implications on wild species resident in that area. Bivalve molluscs can exert pressure on wild species at a number of levels including; habitat formation (suspended structures, trestles, reef formation), deposition of organic waste (faeces and pseudofaeces, organic enrichment), nutrient addition (excretion) and removal (harvest), antifouling treatments, disease spread (see Table 1), introduction of non-indigenous species (NIS), unintended spread of hitch-hiker species (external and internal), competition for seston / phytoplankton, control of phytoplankton (biomass, size), predation on planktonic life-stages, ecosystem services (control of eutrophication). Having noted those possible complications, a proper examination of the potential for any of these manifesting in the receiving area may reduce the possibility of their occurrence to non-significant levels.

Specific examples have been highlighted in Table 2, which is not an exhaustive list but includes some examples of interactions and implications between transferred bivalves and wild fish stocks. The magnitude of these interactions and mitigation measures have been added where possible. The magnitude of these interactions could be considered by calculating the vulnerability of the receiving water body to a NIS (group of species or potential hitch-hikers); (Gittenberg pers comm.). Gaps in scientific knowledge decrease the success of this method. Gaps in knowledge exist at a number of levels, for example, lack of knowledge on the life cycles of even the best known bivalve pathogenic agents (e.g. *Marteilia* sp. and *Bonamia ostrea*) has hindered any breakthrough in controlling these diseases (Mortensen 2006, Moyer *et al.* 1993, van Banning 1990).

Bivalves act as both the host and vectors for the transfer of microparasites and diseases (see Table 1). Parasites can produce important economic losses for aquaculture products, not only from direct mortalities but also due to decrease in growth, high susceptibility to other opportunistic pathogens, increase of stress or parasitic castration. Thus, the high density of the stock used in aquaculture, together with the operating procedures, produces a stress that increases the development of infectious diseases. The incidence of parasites is related to the culture system used. In open systems, marine cages or bivalve culture systems it is difficult to control and in most cases treatments are not possible. Therefore in order to control and combat infectious it is important to work on the; knowledge of the life cycle of parasites, development of specific treatments, study of genes involved in immune response in order to select resistant strains or include methods for the improvement of immune response to pathogens (Gestal *et al.* 2008). Gaps in knowledge exist in these areas for certain species. Further areas to develop to further reduce and control spread of disease include; improve treatment and prevention, eliminate of infected individuals, better control of

stock movement (by applying a zonification policy to control movement of stocks), and improve quarantine and stress reduction.

Pathogens always produce negative impacts. In order to carry out a risk analysis we have to study each species and each environmental situation. In relation to molluscs, the World Organisation of Animal Health (OIE) list currently identifies a total of 8 noticeable diseases: bonamiosis (*Bonamia exitiosa*, *B. Ostreae*), marteiliosis (*Marteilia refringens*), Perkinsosis (*Perkinsus marinus*, *P. olsenii*), infection with *Xenohaliotis californiensis*, herpesviriosis (infection with abalone herpesvirus and oyster infection with herpesvirus-1 microvariant) (OIE, 2014). In addition, in 2006 the EU published a directive on animal health conditions (European Union Council Directive 2006/88/CEE: On animal health conditions for placing on the market, importation and transit of aquaculture animals and their products, and on minimum measures for the prevention and control of certain diseases in aquatic organisms). In this directive there is a list of noticeable diseases, including non-exotic (*Marteilia refringens* and *Bonamia ostreae*) and exotic (*Perkinsus marinus*, *Bonamia exitiosa* and *Mikrocytos mackini*) species.

At present there are no clear conclusions concerning the interaction between wild and farmed shellfish. The EFSA report (2007) pointed out that:

“a recent review (Mortensen *et al.*, 2007, cited in EFSA report 2007) provides valuable information concerning infectious diseases interactions between wild and farmed fish, shellfish and crustaceans in Europe. For mollusc diseases this review emphasized only circumstantial evidence of pathogen exchange between wild and farmed populations. Pathogen exchange are mainly suspected but rarely demonstrated while lots of evidence of transmission from farm to farm exist. There is some evidence of transmission from wild to farm but little evidence of transmission from farm to wild and even less evidence that this resulted in diseases. Knowledge on mollusc parasites life-cycle is limited and this missing information implies that demonstration of transmission between wild and farm shellfish more difficult.”

However, Johansen *et al.* (2011) also point out the importance of pathogen exchange between wild and farmed fish population in Norway.

Hatcheries typically produce diploid shellfish seed. They can also produce triploid spat, which is considered by some not to be a safe genetic confinement tool as triploids may occasionally breed. Another gap in knowledge exists concerning the effect of the partial sterility of triploids, although expertise does exist on the risk, e.g. biovigilance survey program in France. A possible threat to wild populations is the use of tetraploid broodstock if they escape from quarantine, as their fitness relative to diploids and the impact of their breeding with diploids is still unknown (GEN-IMPACT 2007). Another impact has recently been recognised resulting from the reproduction and spread of Pacific oysters in the wild, invading ecosystems to replace indigenous species and causing a problem to shellfish farmers because of extensive wild and uncontrolled spatfall. This non-indigenous species which was originally introduced to enhance and expand aquaculture production has become established in many European countries to the extent of now being considered a pest, not only to farmers and wild fisheries, but also by leisure industries with impacts on beaches and pier areas. This said, *C. gigas* has become the basis for the majority of the commercial harvest of oysters in many of the EU countries. The balance between an immense economic gain and food source may weigh heavily on the acceptance of the introduction, as it does in the Pacific Northwest of the US.

Hard clam or Northern Quahog (*Mercenaria mercenaria*) aquaculture on the East Coast of North America has existed for almost 40 years. It began because natural populations were decreasing and baymen wanted to continue to work on the water. Based on hatchery seed, the industry has grown in many states from Maine to Florida. The cultured clam is grown in areas where the species had previously existed. There has been some movement of clams from one state to another with some impact. The greatest impact occurred when seed from southern hatcheries (warmer climate) were sold to northern growers. As the clams approached market size, the cold weather of the northern climates weakened the clams and they died. That kind of transfer of seed from south to north does not happen now because of this mortality event (Flimlin, pers.comm.).

The hatchery process for the Northern Quahog has selected for fast growers over time. This is not a genetic modification but only a choosing of a more robust individual for reproduction. The other selection has been the use of the notata strain of the clam. This strain, which occurs about 2% of the time in nature, causes a zig-zag marking of the shell, and was used to differentiate the cultured clam from the wild clam, to thwart poaching of the cultured clam. If the selected characteristics were to transfer to the wild stock, they would only manifest in faster growing wild clams, and a slight increase of the notata marking, neither of which has been noticed in a significant way by industry or researchers (Flimlin, pers.comm.).

The gap in knowledge concerning hybridisation is gradually improving as information on the distributions of mussel species and their hybrids is being documented (Dias *et al.* 2008a; 2008b). Without this basic information it is impossible to estimate the genetic influence of mussel aquaculture on wild populations (Beaumont 2000). Conversely, advances in scientific knowledge could influence results in another way, for example, advanced monitoring through the development of improved underwater photography may result in the discovery of NIS in areas, hitherto not found. This may skew results suggesting a recent increase in NIS introductions but may be an artefact of the improved ability to monitor the environment rather than a real change. It is important to realise that gaps in knowledge exist at many levels and these influence our findings and conclusions. Advances in technology may improve monitoring processes however it will not be possible to compare new results with historical datasets.

Legislation exists in most of the ICES countries to control shellfish movements and local screening methods are in place.

Table 2: Potential effects and consequences of bivalve transfers for mariculture.

Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
To develop the stock and new habitats	Intentional transfers or introductions	<i>Crassostrea gigas</i> (WGITMO 2009) effect biological diversity and function of receiving system	Create new habitat	Out-compete native species	Europe, U.K
			Ecosystem services	Hitch-hikers (pest and disease carriers, eg. Oyster Herpes Virus, OHV-1 and OsHV-1 μ var)	France, Ireland, The Channel Island of Jersey
	Unintentional transfer of fouling organisms	<i>Styela clava</i> (tunicate) (Davis and Davis 2010)		Competes with native and commercial bivalves for space	Europe, UK
		<i>Didemnum vexillum</i> (Beveridge <i>et al.</i> 2011)		Nuisance species, ecological and economic	UK
Transfer of macro-parasites and pests (associated species living on the shells of introduced or transferred bivalves)	"stowaways" on mechanical vectors	<i>Polydora ciliata</i> on mussels, oysters, scallops and clams (Kent 1979)		Weaken shell, increase energy demand, decline in reproduction, increased mortality	UK
		A number of other macro parasites from the		Range of impacts.	

		German Bight eg. <i>Mytilicola</i> spp. with a range of impacts (Thieltges 2006). Trematode metacercariae		Reduce growth, general health, reproduction and feeding, potential economic impact.	Germany
Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
Transfer of macro-parasites and pests (associated species living on the shells of introduced or transferred bivalves)	“stowaways” on mechanical vectors	American Oyster Drill, <i>Urosalpinx cinerea</i>		Predates native and commercial oyster beds	Netherlands
		Slipper Limpet, <i>Crepidula fornicata</i> (Blanchard, 1997)		Out-compete native bivalves	France, Spain, UK
Transfer of biotoxins, cysts, larvae and eggs (associated species present in the intervalval water of introduced or transferred species)	Bivalves have the potential to accumulate algal toxins	Accumulate Dinoflagellates, diatoms, nanoflagellates and cyanobacteria (Jiang <i>et al.</i> 2006)		Human disease associated with algal toxins	World wide
	Bivalves translocate resting cysts of toxic algae	Vector for distribution of reproductive cysts of toxin producing algae (intervalval water) (Brenner <i>et al.</i> 2014)		Human health risks, fishery and culture closures and commercial loss	World wide

Transfer of micro parasites and diseases (listed under the mandate of the World Organisation of Animal Health (OIE, 2010) and current shellfish health legislation (EC/2006/88))	Bivalves as host	<i>Marteilia</i> spp.		<i>Marteiliosis</i>	Ireland
	Bivalves as vector	<i>Marteilia refringens</i> affecting <i>Ostrea edulis</i> and mussels		<i>Marteiliosis</i>	France, Spain
Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
Transfer of micro parasites and diseases (listed under the mandate of the World Organisation of Animal Health (OIE, 2014) and current shellfish health legislation (EC/2006/88))	Bivalves as vector	<i>Bonamia</i> sp. (Des Clers 1991) (<i>B. ostreae</i> in Europe and USA), <i>B. exitiosa</i> in Australia, New Zealand and now in Europe)		<i>Bonamiasis</i> All have a severe effect on host shellfish health	France, Spain, Italy, USA, Australia
		<i>Microcytos</i> spp.		All have a severe effect on host shellfish health	Canada, USA, Australia

		<i>Perkinsus</i> spp.		Major impact on commercial bivalve culture	
		<i>P. marinus</i> (C. virginica, USA		Major impact on bivalve culture	USA
		<i>Xenohaliotis californiensis</i> ,		affecting abalone species i	USA, Europe, Chile, Japan
		MSX Haplosporidian nelsoni		Major impact on commercial bivalve culture	USA
		<i>P. olsenii</i> (<i>R. decussatus</i> , <i>R. philippinarum</i> in Europe), Haliotis in USA, Australia, Korea, New Zealand)			Europe, Usa, Australia, Korea, New Zealand
		<i>Haplosporidium</i> sp (in <i>R. decussatus</i> , <i>R. philippinarum</i> , Haliotis in Europe)			Europe
	Virus transfer	Oyster Herpes Virus, OHV-1 and OsHV-1 μ var			France, UK, Spain, Italy, Portugal, Australia, Japan
		Fish pathogenic viruses (IPNV) (Mortensen 1993)			
Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
Transfer of micro parasites and diseases	Virus transfer e.g. <i>C. gigas</i> (NIS act as a vector for novel diseases)	Virus causing gill disease		Eradicate the susceptible population of Portuguese	France

(listed under the mandate of the World Organisation of Animal Health (OIE, 2010) and current shellfish health legislation (EC/2006/88))		(Comps 1988)		oyster, <i>C. angulata</i> from the French Coast	
Transfer of human pathogenic agents bacteria and viruses	Bivalves as vector for bacteria concentrated in the digestive gland	<i>Salmonella</i> spp. (Hernroth 2003)		Enterocolitis, enteric fevers (typhoid and septicaemia)	World wide
		<i>Vibrio</i> bacteria (Shao 2001, Blake <i>et al.</i> 1979)		Severe infections	
	Bivalves as vector for viruses concentrated in the digestive gland	Norovirus (Gantzer <i>et al.</i> 1998)		Gastroenteritis	
		HAV (Lees 2000, Salamina and D' Argenio 1998)		Serious	Italy
Genetic effects of transfers	Risk of hybridisation				
	e.g. Scallops	<i>Argopecten irradians</i> from USA to China		Hybridisation is unpredictable, can lead to loss of genetic diversity (Beaumont 2000)	

Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
Genetic effects of transfers	e.g. Scallops	<i>Patinopecten yessoensis</i> from Japan to Canada		Introductions breeding with indigenous stock could result in reduced fecundity	Canada
	e.g. Oysters	<i>Crassostrea gigas</i> in Europe		Hybrids found	Europe
		<i>Crassostrea gigas</i> in Taiwan		Hybrids found	Taiwan
		European <i>Ostrea edulis</i> to USA and Canada		Reduced variability	USA, Canada
	e.g. Mussels	<i>Mytilus edulis</i> , <i>Mytilus galloprovincialis</i> overlap in distribution. <i>Mytilus trossulus</i> in discrete areas.		Where 2 or more of these species occur together hybrids are found (Knowledge gap) (Dias <i>et al.</i> 2008a, b) eg. Scotland, hybrids occur. Growers trying to manage out the fragile shelled <i>M. trossulus</i>	Scotland
Impact of transfer on biodiversity	Introduction	<i>C.gigas</i> to Ireland		Hitch-hikers, potential disease carriers (Minchin, 1993, 1996, 2013)	Ireland

Topic	Transfer/ introduction	Example	Positive Impact	Negative Impact	Country impacted
Impact of transfer on biodiversity	Introduction	<i>C. gigas</i> expansion in Northern European latitudes		Habitat heterogeneity reduced over large spatial scales, Risk of transfer of OsHV-1 μ var	Europe
		<i>Ruditapes philippinarum</i> , clam species from Asia to France in 1980's		By 1990's <i>R. philippinarum</i> more abundant than the native clam, <i>R. decussatus</i> . Gap in knowledge as to how it outcompetes the indigenous clam?	France
		<i>Crepidula fornicata</i> , UK and France		Outcompete natural fauna, destroy ecosystems (Blanchard 1997)	UK, France

References

- Ambariyanto, Seed, R. 1991. The infestation of *Mytilus edulis* Linneaus by *Polydora ciliata* (Johnston) in the Conwy estuary, North Wales. *J. Moll. Stud.* 57, 413–424.
- Beaumont, 2000. Genetic considerations in transfers and introductions of scallops. *Aquaculture International*, 8, 493-512.
- Beveridge, C., Cook, E.J., Brunner, L., MacLeod, A., Black, K. Brown, C. & Manson, F.J. (2011). Initial reponse to the invasive carpet sea squirt, *Didemnum vexillum*, in Scotland. Scottish Natural Heritage Commissioned Report No. 413.
- Blanchard, M. 1997. Spread of the slipper limpet *Crepidula fornicata* (L. 1758) in Europe. Current state and consequences. *Sci. Mar.* 61 (Sup 2), 109-118.
- Blake, P.A., Merson, M.H., Weaver, R.E., Hollis, D.G., Heublein, P.C. 1979. Disease caused by a marine vibrio: clinical characteristics and epidemiology. *N. Engl. J. Med.* 300, 1-5.
- Brenner, M., Fraser, D., Nieuwenhove, K. Van, O'Beirn, F., Buck, B.H., Mazurié, J., Thorarinsdottir, G., Dolmer, P., Sanchez-Mata, A., Strand, O., Flimlin, G., Miossec, L., Kamermans, P. (2014) Bivalve aquaculture transfers in Atlantic Europe. Part B: Environmental impacts of transfer activities. *Ocean & Coastal Management* 8, 139-146
- Calvo-Ugarteburu, G., McQuaid, C. D. 1998. Parasitism and invasive species: effects of digenetic trematodes on mussels. *Mar. Ecol. Prog. Ser.* 169, 149 - 163.
- Camacho, A., Villalba, A., Beiras, R., Labarta, U. 1997. Absorption efficiency and condition of cultured mussels (*Mytilus edulis galloprovincialis* Linneaus) of Galicia (NW Spain) infected by parasites *Marteilia refringens* Grizel *et al.* and *Mytilicola intestinalis* Steuer. *J. Shellfish Res.* 16, 77 -82.
- Carrasco, N., Villalba, A., Andree, K.B., Engelsma, M.Y., Lacuesta, B., Ramilo A., Gairín, I., Furones, M.D. (2012) *Bonamia exitiosa* (Haplosporidia) observed infecting the European flat oyster *Ostrea edulis* cultured on the Spanish Mediterranean coast. *Journal of Invertebrate Pathology* 110 (2012) 307–313
- Comps, M. 1988. Epizootic diseases of oysters associated with viral infections. In: *Disease Processes in Bivalve Molluscs*. American Fisheries Society Special Publication 18 (ed. W.E. Fisher), Bethesda, USA, pp. 23–37.
- Davis, M. H. and Davis, M. E. (2010). The impact of the ascidian *Styela clava* Herdman on shellfish farming in the Bassin de Thau, France *Journal of Applied Ichthyology* 26:12-18
- Des Clers. 1991. Models for a *Bonamia ostreae* epidemic in a cohort of cultured European flat oysters, *Ostrea edulis*. *Aquaculture* 93: 253-262
- Desclaux, C., de Montaudouin, X., Bachelet, G. 2004. Cockle *Cerastoderma edule* population mortality: role of the digenean parasite *Himasthla quissetensis*. *Mar. Ecol. Prog. Ser.* 279, 141– 150.
- Dethlefsen, V. 1975. The influence of *Mytilicola intestinalis* Steuer on the meat content of the mussel *Mytilus edulis* L. *Aquaculture* 6, 83 - 97.
- Dias, J., Snow, M. and Davies, I. 2008a. Understanding the distribution of mussels (*Mytilus* species) in cultivation and wild populations in Scotland. *Fish Farmer*, October 2008.
- Dias, P.J., Sollelis, L., Cook, E.J., Piertney, S.B., Davies, I.M. and Snow, M. 2008b. Development of a real-time PCR assay for detection of *Mytilus* species specific alleles: Application to a sampling survey in Scotland. *Journal of Experimental Marine Biology and Ecology* 367, 253 - 258
- European Directive 2006/88/EC Official Journal of the European Union 24.11.2006 (OJ No L328/14 24.11.2006)

- Gantzer, C., Maul, A., Audic, J.M and Schwartzbrod, L. 1998. Detection of infectious enteroviruses, enterovirus genomes, somatic coliphages and Bacterioides fragilis phages in treated wastewater. *Appl Environ Microbiol* 64, 4307- 4312.
- GENIMPACT (2007) Genetic impact of aquaculture activities on native populations. Svåsand T, Crosetti D, García-Vázquez E, Verspoor E (eds). Genimpact final scientific report (EU contract n. RICA-CT-2005-022802), 176 pp.
- Gestal, C., Roch, P., Renault, T., Pallavicini, A., Paillard, C., Novoa, B., Oubella, R., Venier, P. and Figueras, A. (2008) Study of Diseases and the Immune System of Bivalves Using Molecular Biology and Genomics, *Reviews in Fisheries Science*, 16: 1, 131 - 154
- Hernroth, B. 2003. Factors influencing bactericidal activity of blue mussel (*Mytilus edulis*) haemocytes against *Salmonella typhimurium*. *Fish Shellfish Immunol.* 14, 93-104.
- ICES. 2006. Report of the Working Group on Introduction and Transfers of Marine Organisms (WGITMO), 16–17 March 2006, Oostende, Belgium. ICES CM 2006/ACME: 05: 334 pp
- ICES. 2009. Report of the Working Group on Introduction and Transfers of Marine Organisms (WGITMO), 11–13 March 2009, Washington D.C., USA. ICES CM 2009/ACOM: 25: 220 pp
- ICES. 2011. Report of the Working Group on Introduction and Transfers of Marine Organisms (WGITMO), 16–18 March 2011, Nantes, France. ICES CM 2011/ACOM: 29: 162 pp
- ICES. 2011. Report of the Working Group on Marine Shellfish Culture (WGMASC), 5 – 8 April 2011, La Trinité-sur_Mer, France. ICES CM 2011/SSGHIE:
- ICES. 2012. Report of the Working Group on Marine Shellfish Culture (WGMASC), 20–23 March, Sopot, Poland. ICES CM 2012/SSGHIE: 15, 117 pp.
- Jiang, T-J., Tao Niu, T. and Xu, Yi-X., (2006) Transfer and metabolism of paralytic shellfish poisoning from scallop (*Chlamys nobilis*) to spiny lobster (*Panulirus stimpsoni*). *Toxicon* 48 (2006) 988–994
- Johansen, L. -H, Jensen, I., Mikkelsen, H., Bjørn, P.-A., Jansen, P.A., Bergh, Ø., Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway. *Aquaculture* 315 (2011) 167–186
- Kent, R.M.L. 1979. The influence of heavy infestations of *Polydora ciliata* on the flesh content of *Mytilus edulis*. *J. Mar. Biol. Assoc. UK.* 59, 289 - 297
- Lees, D. 2000. Viruses in bivalve shellfish. *Int. J. Food Microbiol.* 59, 81-116
- Minchin, D., Duggan, C.B., Holmes, J.M.C. and Neiland, S. 1993. Introductions of exotic species associated with Pacific oyster transfers from France to Ireland. International Council for the Exploration of the Sea, Copenhagen (Denmark). Mariculture Comm. Counc. Dublin, Ireland, 23 Sep-1 Oct 1993, 11, CM 1993/F:27.
- Minchin, D. 1996 Management of the introduction and transfer of marine molluscs, *Aquatic Conservation: Marine and Freshwater Ecosystems*, Volume 6 (4), 229–244.
- Minchin, D., Cook, E.J. and Clark, P.F. (2013). Alien species in British brackish and marine waters. *Aquatic Invasions*, 8, Issue 1: 3–19
- Mortensen, S.H. 1993. Passage of infectious pancreatic necrosis virus (IPNV) through invertebrates in an aquatic food chain. *Diseases of Aquatic Organisms* 16, 41 - 45.
- Mortensen, S., Korsnes, K. and Bergh, Ø. 2006. “Eyes Wide Shut” A critical view of aquaculture health management and risk factors in the “real world”. *Bull. Eur. Ass. Fish Pathol.* 26(1), 2.
- Moyer, M.A., Blake, N.J. and Arnold, W.S. 1993. An ascetosporan disease causing mass mortality in the Atlantic calico scallop, *Argopecten gibbus* (Linnaeus, 1758). *Journal of Shellfish Research* 2, 305 - 310.
- OIE 2014. <http://www.oie.int/en/animal-health-in-the-world/oie-listed-diseases-2014/>

- Ramilo, A., Navas, J.I., Villalba, A., Abollo, E., (2013) Species-specific diagnostic assays for *Bonamia ostreae* and *B. exitiosa* in European flat oyster *Ostrea edulis*: conventional, real-time and multiplex PCR. *Diseases of Aquatic Organisms*, Vol. 104: 149–161, 2013
- Salamina, G., D'Argenio, P. 1998. Shellfish consumption and awareness of risk of acquiring hepatitis A among Neapolitan families - Italy, 1997. *European Surveillance* 3, 97- 98
- Scientific Opinion of the Panel on Animal Health and Welfare on a request from the European Commission on possible vector species and live stages of susceptible species not transmitting disease as regards certain mollusc diseases. *The EFSA Journal* (2007) 597, 1-116
- Shao, Z.J. 2001. Aquaculture pharmaceuticals and biologicals: current perspectives and future possibilities. *Adv. Drug Delivery Rev.* 50, 229 - 243
- Taskinen, J. 1998. Influence of trematode parasitism on the growth of a bivalve host in the field. *Int. J. Parasitol.* 28, 599 - 602.
- Thieltges, D.W. 2006. Effect of infection by the metacercarial trematodes *Renicola roscovita* on growth in the intertidal blue mussel *Mytilus edulis*. *Mar. Ecol. Prog. Ser.* 319, 129-134.
- van Banning, P. 1990. The life cycle of the oyster pathogen *Bonamia ostreae* with a presumptive phase in the ovarian tissue of the European flat oyster, *Ostrea edulis*. *Aquaculture* 84, 189 - 192.
- Wegeberg, A., Jensen, K. 1999. Reduced survivorship of *Himasthla* (Trematoda, Digenea)-infected cockles (*Cerastoderma edule*) exposed to oxygen depletion. *J. Sea Res.* 42, 325 - 331.
- Wegeberg, A. M., Jensen, K. 2003. In situ growth of juvenile cockles, *Cerastoderma edule*, experimentally infected with larval trematodes (*Himasthla interrupta*). *J. Sea Res.* 50, 37 - 43
- Wolff, W.J. and Reise, K. 2002. Oyster imports as a vector for the introduction of alien species into Northern and Western European coastal waters. In *Invasive aquatic species of Europe: distribution, impacts and management*. Edited by E. Leppäkoski, S. Gollasch and S. Olenin. Kluwer Academic Publishers, Dordrecht. pp. 193 - 205.

4.1.2 Escaped Fish (Terje Svåsand, Norway)

4.1.2.1 Magnitude of escapes

Fish may escape at any stage of development, from eggs and gametes through juvenile to adult stages (Cross *et al.*, 2008). There are different causes of the escapes (Jensen *et al.*, 2010), and the chances for survival are very dependent on the stage that escapes, on season, location, etc., as are the potential impacts (e.g. Skilbrei, 2010a, b; Olsen and Skilbrei 2010). Escapes of fishes from net pens may be considered as either chronic or acute (Bridger and Garber, 2002). Chronic escapes are the “leakage” of fish from culture sites resulting from improper farm practices (e.g., dropping fish during transfers), small holes in containment netting, escapes by sub-size individuals through netting, etc. In contrast, acute losses are massive losses due to holes torn by predators or damage due to storm events that may result in near or total loss of fish in net pens.

In general, the number of fishes escaping from fish farms is poorly known. Estimates range from less than 1% to greater than 6% of the fish in sea cages, depending on species, size, etc. (Leggatt *et al.*, 2009; Moe *et al.*, 2007; Thorstad *et al.*, 2008). Although known losses must be reported in most jurisdictions, the number of losses is likely underreported in official statistics. Skilbrei and Wennevik (2006) suggested that the majority of aquaculture escapees they caught in a study to evaluate the provenance of salmon in Norway appeared to result from small, unreported escape events. In a recent ongoing study, Skilbrei *et al.*, (in prep) estimated that the actual total number of

smolt and adult escapees is 2–5 times higher than the numbers reported to the authorities by the fish farmers for the period. Unnoticed escapes of smolts due to too small mesh sizes were suggested as one of the causes for these differences.

Escape rates are likely to be size- or stage-specific as well as species-specific. For example, Atlantic cod (*Gadus morhua*) are presumed to have greater potential to escape than do salmon because of the propensity of the former to bite on and through netting and its willingness to enter openings (Moe *et al.* 2007; Jensen *et al.*, 2010).

Some of the escaped fish survive and become ecologically important in the functioning of the surrounding ecosystem. For example, Fiske *et al.* (2001) suggest that farmed salmon may outnumber wild salmon in a number of Norwegian rivers and averaged between 26 and 40% of the sea fishery for salmon in 2 areas between 1993 and 1999 because of the relatively large number of escapes. Despite the relatively small size of the Atlantic salmon culture industry in eastern Canada (compared to Norway), given the reduced abundance of natural stocks in eastern north American Rivers (e.g., Amiro, 2003), escaped farmed individuals may also be more abundant than wild salmon in rivers in this area (Thorstad *et al.*, 2008). They may also be present in areas where the species is not normally found, such as western North America and Chile (Morton and Volpe, 2002; Soto *et al.*, 2006).

The abundance of escaped fishes are influenced by the abundance of farm sites or total number of fish being farmed in an area (Fiske *et al.*, 2006), although farmed fish may also disperse over large areas (Hansen 2006; Skilbrei *et al.* 2010b; Hansen and Youngsson 2010). The location of the fish farm is important for the dispersal of the escapees. Adult salmon escaping from farms in fjords may reside in the area for weeks or even months (Skilbrei *et al.* 2010). Experience indicates that escaped fish spread more rapidly from farms at more exposed localities at the outer coast.

A number of fish species grown in cage culture in OSPAR countries may also contribute individuals to the natural environment via the release of gametes from individuals spawning within culture facilities. This includes Atlantic cod and European sea bass (*Dicentrarchus labrax*). In some instances, the contribution of individuals of the former species via this pathway to wild stocks may also be substantial (e.g., Jørstad *et al.*, 2008).

Given that the number of different farmed fish species may greatly outnumber the wild populations at the local level, even relatively small escapes may have important effects on local or wider-scale fish populations (Youngson *et al.*, 2001). It is also clear that the number of farmed fish escaping may be large compared to the natural wild conspecifics.

4.1.2.2 Survival, dispersal, and migration of escaped fish

In order to have an impact on the surrounding ecosystem, fish escaping from culture sites must first survive. Surviving fish may then disperse from culture areas and perhaps undergo migrations. Each of these processes is quite variable and a function of the stage of fish that is released/escapes and the time of year/development at which this occurs. Thorough reviews of these processes for Atlantic salmon are provided by Weir and Fleming (2006), Thorstad *et al.* (2008), Skilbrei 2010a, b and the ICES WGNAS (2010); only a brief summary is provided here.

In general, farmed Atlantic salmon in the initial freshwater phase of their life cycle have reduced survival relative to wild conspecifics, as shown by Einum and Fleming (2001) in a meta-analysis of the existing data. This is considered to be a function of

farmed fish being less well adapted to the receiving environment in terms of both genetic fitness and also due to their having been reared under hatchery conditions.

In general, Atlantic salmon smolts released into rivers migrate quickly downstream to the sea (Jonsson and Jonsson, 2006). Smolts from hatcheries that escape from marine sites will return to release areas and migrate up local rivers to spawn (Eriksson and Eriksson, 1991; Jonsson, 1997; Skilbrei 2010b). Post-smolts released in the winter show poor survival and homing ability (Hansen and Jonsson, 1991). The former may be due to harsher winter conditions (less food, etc.) when natural populations have migrated away to areas with more clement conditions (Weir and Fleming, 2006). One study in Norway (Jonsson *et al.*, 1993) found that released post-smolts migrated away from release sites with the predominant current at a rate of ca. 1.6 km day⁻¹ but at a rate of ca. 7.5 km day⁻¹ when moving along the open coast. Similarly, Skilbrei *et al.* (1998, cited in Thorstad *et al.*, 2008) found that salmon released in an open coastal area with strong currents dispersed more widely than did fish released in areas without strong coastal currents. Salmon released in the autumn prior to attaining sexual maturity have poor survival whereas those released later in the winter had greater survival (Hansen *et al.*, 1987). Adult farmed salmon seem to move away from farm sites quite quickly (Whoriskey *et al.* 2006; Skilbrei *et al.* 2010; Chittenden *et al.* 2011). These studies also found that mortality of these fish was high and experimental fish very rarely returned after a year or more at sea to spawn in neighbouring rivers. The risk of escaped salmon entering river appears to be higher if they are mature at the time of escape, then they may move rapidly from the fish farm towards the river mouth (Heggberget *et al.* 1993). In general, the “attractiveness” of a river for escaped farm salmon is scale-dependent with larger rivers attracting more escaped fish, even though they may be distant from release sites (Thorstad *et al.*, 2008).

Survivorship of escaped adult salmon varies among locations and release dates. Hansen and Jacobsen (2003) found that recapture rates of tagged farm fish released in the winter were greater for those than those released in autumn. A second study done at 2 salmon farms in Norway (Hansen, 2006) found that escaped farmed fish recapture rates increased with the season with fish released in November being recaptured at a rate of only 0.2% whereas those released in March/April were recaptured at a rate of about 5%. In all cases, survival of farmed salmon is less than that of similar-aged wild conspecifics (Jonsson and Jonsson, 2006; Kostow, 2004; Thorstad *et al.*, 2008; Weir and Fleming, 2006). However, all the papers describing releases of adult salmon report primarily recaptures from the first months post-releases, which basically reflect the fishing effort in the release area and the dispersal rate of the fish. If adult immature fish are released in fjords with a high fishing effort the recapture rate may be rather high, from 30 – 70 % (Skilbrei and Jørgensen 2010; Chittenden *et al.* 2011). Green *et al.* (2012) assessed Scottish angler catch data and demonstrated that there was no significant contribution of escapees to the total catch, whilst there was a weak positive correlation with increased trout catches with local escape events - which was proposed as being the opposite of what would be expected if escapes were a detriment to wild stocks.

In general, farmed salmon escaping from sites in the NE and NW Atlantic and the Pacific may disperse over large spatial scale, at times being recovered thousands of km from release sites. Rainbow trout (*Oncorhynchus mykiss*), on the other hand, disperse much more slowly and may also reside for long periods in the general farm area (Bridger *et al.* 2001; Skilbrei 2012; Patterson and Blanchfield 2013). Migration into rivers by escaped farmed salmon lacking experience with their home river is often delayed relative to wild conspecifics (Jonsson *et al.*, 1990; Jonsson *et al.*, 1994) and may

occur after wild salmon (Lund *et al.*, 1991). Most escaped salmon recaptured in sea during autumn is immature (Skilbrei and Wennevik 2006). However, if salmon are close to maturity when they escape, a large proportion of them may migrate successfully into local riverine systems over a short period of time. For example, Heggberget *et al.* (1993) found that 51% of “escaped” farm salmon migrated into a local (2 km distant) river within about 4 days of being released. Although, Økland *et al.* (1995) found that farmed Atlantic salmon may stay in rivers for less time than do wild conspecifics, this is not always the case and other studies have found that the two groups do not differ in river residence times for spawning (Thorstad *et al.*, 1998). This latter study also indicated that farmed salmon may also undertake more within river movements during the spawning season than do wild salmon. A number of studies have also shown that farmed salmon may be distributed more randomly than are wild fish (Power and McCleave, 1980; Heggberget *et al.*, 1993) or occupy areas upstream (Thorstad *et al.*, 1998) or downstream (Power and McCleave, 1980) of wild conspecifics. Fleming *et al.* (2000) suggest that this may be due to farmed salmon lacking natural river imprinting or else being competitively inferior.

Taken together, it seems that the older a fish is when it escapes the more likely it may be recaptured. However, the majority is immature fish those are recaptured in sea relatively soon after their escape. Therefore, the link between escapements of adult salmon and the risk of fish entering rivers are not very clear unless the fish has started to mature at time of the escape. The long term survival of adult escapees is probably very low, also compared with the performance of escaped smolts. Hence, escaped farmed salmon in rivers is probably a mix of newly escaped mature adult salmon and former smolt escapees with a dominance of the first group since escape statistics indicate that most escapees are adults.

4.1.2.3 Overview of impacts due to escapes

Issues not covered by the WGAQUA: The best studied of all potential impacts due to aquaculture escapes is that of genetic effects operating at a variety of levels. Indeed, a number of reviews and risk assessments have been done on this subject, especially as they relate to Atlantic salmon (e.g., Naylor *et al.*, 2005; Cross *et al.*, 2008; Svåsand *et al.* 2007; Glover *et al.* 2013). In short, escaped individuals or genetic material (i.e., eggs and/or sperm) from farm sites may mix with wild stock and decrease the overall fitness of the different populations. This has been shown from both theoretical and empirical studies. These issues are covered further by the WGAGFM. Another issue of importance with respect to fish farm sites is the potential transfer of diseases from fish cage sites to fishes in the surrounding environment (Costello, 2009; Serrallinares, 2014). These issues are covered below in the section on “Transmission of sea lice and other parasites to wild populations” and by the WGPDMO for other pathogens.

Physiological, morphological and behavioural differences in farmed relative to wild fish: All life stages of farmed fish may differ from those counterparts in the wild (Svåsand *et al.*, 1998; Jonsson and Jonsson, 2006). This is due to genetic selection for sought traits (e.g., fast growth: Solberg *et al.*, 2013), manipulations (e.g., triploid individuals: Fraser *et al.*, 2013) or else because the farm environment exerts specific developmental forces that may force different phenotypes or behaviour (Svåsand *et al.* 1998). For example, the protected environment in which farmed fish are raised allows them to invest more of their consumed energy into protein growth and fat deposition, resulting in a number of morphological changes (Thorpe, 2004). These include smaller heads, rayed fins, and caudal peduncles in Atlantic salmon parr (Fleming *et al.*,

1994; Cramon-Taubadel *et al.*, 2005), and altered expression of secondary sexual characteristics in coho salmon (Hard *et al.*, 2000). A number of other fish species, including Atlantic cod, also show precocious maturation under aquaculture conditions (Hansen *et al.*, 2001). Such changes likely influence their survival ability if escaped as well as their potential impact through interactions with wild fishes and the ecosystem.

Impacts on other fish species due to escapes: We have identified 3 potentially important consequences of escaping fish on other fish species: 1) Predation on wild fish stocks of other species, 2) Competition with wild fish stocks (food/space), and 3) Disease transfer from escaped fish (covered in WGPDMO for other pathogens than sea lice). Unfortunately, very little information is available or was identified in the current review with respect to the impacts of escaping farmed fish on other fish populations. The limited information that is available on the consequences of escapees that the WGAQUA are covering (i.e., not genetic issues due to escapees) are almost entirely focused on salmon escapees and their interactions on and with conspecifics. There is a near-complete lack of information on environmental interactions of escaped non-salmonid fishes from cage culture and wild fish populations. With respect to predation on wild fish stocks of other species, salmon become progressively more piscivorous as they grow and thus will impact some fraction of wild fish populations directly and indirectly through predation and competition for resources. With respect to competition with wild fish stocks (food/space), salmon are generalists in feeding habits and it is generally assumed that the ocean habitat is not limiting for salmon (see below) and thus not likely for their competitors either. Given this, we consider that the risk of escaped salmon to wild fish stocks of other species are typically insignificant with respect to predation and competition and that any effects that may occur are minor, restrained to the areas immediately surrounding farms, and rare – only occurring following massive escapes and only locally. That being said, the uncertainty associated with this is very high as the present review found no discussion on the importance of these effects on wild fish populations.

Effects of escaped salmonids on other salmonid species are covered below in the section on effects on the same species as the literature is often common for the same and differing salmonid species.

Impacts on same species due to escapes: Given the more intense interactions between conspecifics or closely related species (e.g., similar salmon species), there is a greater potential for more and more important interactions between farmed and wild conspecifics and related species than between farmed fish and other fish species. These include: 1) Competition for food, 2) Competition for space, 3) Competition for reproduction, and 4) Disease transfer from escaped fish (covered in WGPDMO for other pathogens than sea lice), and 5) genetic interactions. Genetic interactions between escaped and wild salmonids are very well studied and covered by other groups (i.e., WGAGFM). Below, we outline interactions between escaped farmed and wild fishes of the same species with an emphasis on the former four interactions.

Salmon are typically at the greatest density in the freshwater portions of their lifecycle. Thus there is a greater potential for fry, parr, and smolts to compete than for the returning adults. Overlap in habitat use and diet suggests that farm and wild salmon compete for territories and food (Thorstad *et al.*, 2008, Skaala *et al.* 2013). With respect to feeding, Atlantic salmon are mostly opportunistic feeders on pelagic prey (e.g., Jonsson and Jonsson, 2006). Parr and smolts of farmed/hatchery origin have been shown to outcompete feral salmon in head to head matches for food competition un-

der simulated hatchery conditions but the results were the opposite under simulated natural conditions (Einum and Fleming, 1997; Fleming and Einum, 1997) and a number of studies have shown that this may be due to a greater aggressiveness in farmed fish (Jonsson and Jonsson, 2006). McGinnity *et al.* (2003) have also shown that faster-growing hatchery-derived salmon may displace smaller wild salmon downstream. In contrast, Fleming *et al.* (2000) found that farmed salmon were distributed further upstream of wild salmon than would have been expected based on the distribution of nests by wild and farmed females. In sum, effects of escaped juveniles in rivers with respect to competition for food and space are both expected to be minor with a “likely” likelihood and there is very low uncertainty about this given the multiple papers addressing the subject. This yields a risk ranking of moderate with very low uncertainty for the impact of escaped salmonids on wild conspecifics in the first freshwater phase with respect to competition for food and space.

Once in the sea, a number of studies (e.g., Lacroix and Knox, 2005) have shown that prey species change along migration routes for Atlantic salmon. Other studies have shown that wild and escaped Atlantic salmon feed on the same prey types. For example, Jacobsen and Hansen (2001) showed that escaped and wild Atlantic salmon fed on similar food types in the Norwegian Sea, north of the Faroe Islands, with younger fish feeding mostly on crustaceans but becoming more piscivorous as they age. This same study showed that diets of both groups shifted by season such that crustaceans *Themisto* spp., euphausiids and mesopelagic shrimps were important in the fall but a variety of fishes became of equal importance later in the winter.

Although escaping farmed salmon logically compete with wild salmon for food in the wild (Naylor *et al.*, 2005; Thorstad *et al.*, 2008), ocean mortality of salmon seems to be density independent, suggesting that the carrying capacity of the ocean habitat has not been reached (Jonsson and Jonsson, 2004). Salmon may be cannibalistic in aquaculture situations and this may account for unaccounted for fish loss in some farm situations (Klemetsen *et al.*, 2003). However, this review found no evidence of cannibalism in wild salmon or between farmed and wild salmon and, if it occurs, it is likely minimal. Consequences due to escaped fish on food resources may also be transitory – immediately following escapes – as Jonsson and Jonsson (2006) conclude from studies on other salmon species in western North America that competition for food between wild and escaped salmon may occur locally where there are large densities of escaped fish. However, analysis of stomach contents of escaped Atlantic salmon captured in coastal areas has shown that 60–96 % of the fish had empty stomachs (Hislop and Webb, 1992; Soto *et al.*, 2001; Morton and Volpe, 2002; Abrantes *et al.*, 2011), and fatty acid profiling has indicated that adult escapees failed to switch to natural prey (Olsen and Skilbrei, 2010; Abrantes *et al.*, 2011). Although this review also found no evidence that escaped salmonids impact wild conspecifics immediately after escapement but this could conceivably occur following massive escapes. Given this, we rate the consequence of escaped salmonids on conspecifics in the areas immediately surrounding farms following massive escape incidents as minor with rare likelihood for an overall risk score of low. Given the lack of published information on this, uncertainty is very high. We rate the consequence of escaped salmonids on conspecifics in the marine phase (post-dispersal from cage sites following escapes) as insignificant with respect to competition for food and space and with rare likelihood, providing a negligible risk rating for escaped salmon once they are in the oceanic phase of their lifecycle. Given that a fair number of studies have addressed this issue we consider the uncertainty associated with this to be very low for consequences, likelihood and thus overall risk.

Once salmon have migrated back to streams and rivers to spawn, the majority of studies have shown that farmed salmon will, all else being equal, typically win competitions with wild fishes for food. Again, this may be because farmed salmon may be more aggressive. However, prior experience with a site by wild fish will shift the balance such that they will win competitions more often than do escaped salmon. Thus, we assign a consequence of this of as minor with a likelihood rating of “likely” and very low uncertainty, yielding an overall risk of moderate with very low uncertainty.

Escaped farmed fish may also compete for mates in natural systems. However, as outlined above, escaped fish may not necessarily overlap with wild fish given that they may occupy different reaches in rivers or spawn at different times of the year. Weir *et al.* (2004) showed that male farmed Atlantic salmon were less able to form dominance hierarchies than were wild salmon. In contrast, farmed salmon courted and spawned with females in greater numbers but frequently failed to release sperm when females released eggs *et al.* (Weir *et al.*, 2004). Taken together, this suggests that farmed males will have lower spawning success than do wild males. A review of spawning success of female Atlantic salmon by Thorstad *et al.* (2008) showed that the number of spawning redds by farmed salmon is often proportional to their relative abundance in rivers suggesting that they are equally successful at spawning as are wild females. However, egg numbers may be reduced. Overall, cultured salmon are competitively inferior to wild salmon and are injured more often than wild ones. That being said, given their greater abundance in some systems, their presence may have a considerable impact on local wild populations (Hindar *et al.*, 2006). This may be particularly true if late-spawning farm escapees destroy redds of wild salmon. Given this potential overlap and competition for breeding sites and mates, we assign a consequence of this of as moderate with a likelihood rating of “likely” and very low uncertainty, yielding an overall risk of moderate with very low uncertainty for the risks of escaped salmonids to competition for space and reproduction in the freshwater reproductive stage of the fish’s lifecycle.

Disease transfer from escaped fish to wild fish of the same species is not well studied and this review found no comprehensive work addressing the subject. We thus assign the consequence of this as minor with rare likelihood but there is very high uncertainty about this as little information on this is available, making for an overall risk score of low.

4.1.2.4 Impacts due to escapes of non-salmonid species

Very little information is available with respect to the consequences, likelihood, or risk due to escapes of non salmonid species from cage culture sites. Most of the available literature deals with how the fish farm, and not the escaped fish, interact with wild fish, and show fish farm may influence wild fish populations in different ways. It is known that fish farms can attract wild fish (e.g. Dempster *et al.*, 2010), sea mammals (Bonizzoni *et al.* 2013) and that fish eating faeces or waste food might influence the quality of the fish (e.g. Otterå *et al.*, 2009). In case of therapeutic food treatments, residues may also be found in the fish living near the farms (e.g. BurrIDGE *et al.*, 2010). Studies also indicate that fish farm may influence the spawning behaviour of fish (e.g. Bjørn *et al.*, 2009).

Of greatest concern is Atlantic cod, which is being increasingly farmed, but it also includes other species, such as European sea bream (www.preventescape.eu). In these species, both adults and propagules from adults breeding in fish cages may escape the confines of farm structures and interact with the fish in the surrounding environment. As expected, escaped farmed cod are predator naïve (Nødtvedt *et al.*, 1999)

and survival of released farmed cod increases with size at release (Kristiansen *et al.*, 2000). Atlantic cod are piscivorous and thus any escaping individuals have some potential to impact wild fish populations. Escaped cod are likely to compete with wild cod for resources and, although they are initially less efficient at capturing wild food (Steingrund and Fernø, 1997), because of large liver energy reserves in escaped farmed cod (Grant *et al.*, 1998; Kristiansen *et al.*, 2000) and the availability of alternative food items (Nordeide and Salvanes, 1991b), they are believed to be able to survive the critical period between escape and adapting to a “wild” mode of existence and overcome an initial foraging disadvantage (Nordeide and Salvanes, 1991a; Salvanes and Braithwaite, 2006). However, given that this species has been greatly reduced in its natural range, it is unlikely that it will have a great impact on wild stocks of the same species through competition as its habitat is unlikely to be limiting. Past stock enhancement experiments with Atlantic cod in Norway showed that mass release of juvenile hatchery-reared cod had minor effects on potential prey organisms for wild cod (Svåsand *et al.*, 2000). Such releases have also been shown to reduce wild cod condition factors and liver index (Fosså *et al.*, 1994), further supporting the notion that releases of farmed fish may impact wild populations through competition for food resources.

By following radio-tagged cod, Brooking *et al.* (2006) suggested that escapees from Atlantic cod farms may increase predation pressure on endangered Atlantic salmon stocks. This notion is further supported by the observations of Wroblewski *et al.* (1996) who tracked radio-tagged farmed cod and found that they associated with wild cod in the ocean and the observations by Hvidsten and Møkkelgjerd (1987) who suggested that natural Atlantic cod populations consumed ca. 25% of the salmon smolts leaving the Surna River in Norway, further suggesting that escaped cod may also impact wild fish populations.

The behaviour of escaped farmed male cod may encourage interbreeding with wild females as farmed males occupy the same depth whereas wild males occupy deeper areas close to the bottom (Meager *et al.*, 2009) and Wroblewski *et al.* (1996) showed that escaped Atlantic cod may migrate to local breeding grounds. However, Skjæraasen *et al.* (2009) found that farmed cod performed poorly against wild cod in sperm competition trials. That being said, using a rare allele as a tracer for farmed cod, Jørstad *et al.* (2008) showed that gametes from farmed fish may produce viable offspring (to the larval stage).

Given the very limited knowledge of such interactions, it is difficult to evaluate the risks associated with Atlantic cod and other types of finfish culture. In short, we believe that, for all risks identified, consequences are minor with rare likelihood but that uncertainty is very high in all instances because of a lack of information for each risk. Thus the overall risk associated with each risk is low with very high uncertainty.

Major Risks of Escaped Fish to Wild Fish Species

- Potentially important consequences of escaping fish on other fish species (besides genetic interaction and disease transfer) can result from:
 - predation on wild fish stocks of other species, and
 - competition with wild fish stocks (food/space).
 - The risk of escaped salmon to wild fish stocks of other species are typically insignificant with respect to predation and competition and that any effects that may occur are minor, restrained to the areas immediately surrounding farms, and rare – only occurring following massive escapes and only locally. That being said, the uncertainty associated with this is very high as the present review found no discussion on the importance of these effects on wild fish populations.
 - There is a near-complete lack of information on environmental interactions of escaped non-salmonid fishes from cage culture and wild fish populations, when not including genetic interaction and spread of pathogens. Earlier stock enhancement studies has indicated limited carrying capacity for Atlantic cod, indicated that large scale escapes may negatively impact wild fish.
 - The consequence of escaped salmonids on conspecifics in the areas immediately surrounding farms following massive escape incidents appear to be minor with rare likelihood of a significant impact. Given the lack of published information on this, uncertainty is very high.
 - The consequence of escaped salmonids on conspecifics in the marine phase (post-dispersal from cage sites following escapes) appears to be insignificant with respect to competition for food and space and with rare likelihood, providing a negligible risk from escaped salmon once they are in the oceanic phase of their lifecycle. Given that a fair number of studies have addressed this issue we consider the uncertainty associated with this to be very low for consequences, likelihood and thus overall risk.
 - Once salmon have migrated back to streams and rivers to spawn, escaped farmed fish may interact with wild salmon. We assign a consequence of this as moderate with a likelihood rating of “likely” and very low uncertainty. The overall risk appears to be moderate with very low uncertainty for the risks of escaped salmonids to competition for space and reproduction in the freshwater reproductive stage of the fish’s lifecycle.
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References

- Abrantes, K.G., Lyle, J.M., Nichols, P.D., and Semmens, J.M. 2011. Do exotic salmonids feed on native fauna after escaping from aquaculture cages in Tasmania, Australia? *Canadian Journal of Fisheries and Aquatic Sciences*, 68: 1539-1551.
- Amiro, P.G., 2003. Population status of inner Bay of Fundy Atlantic salmon (*Salmo salar*), to 1999. *Can. Tech. Rep. Fish. Aquat. Sci.* # 2488: pp. vi + 39.

- Bell, J.G., Waagbø, R., 2008. Safe and nutritious aquaculture produce: benefits and risks of alternative sustainable aquafeeds. in: Holmer, M., Black, K., Duarte, C.M., Marbà, N., Karakassis, I. (Eds.), *Aquaculture in the ecosystem*. Springer-Link, pp. 185-225.
- Bridger, C.J., Booth, R.K., McKinley, R.S., Scruton, D.A., 2001. Site fidelity and dispersal patterns of domestic triploid steelhead trout (*Oncorhynchus mykiss* Walbaum) released to the wild. *ICES J. Mar. Sci.* 58, 510-516.
- Bridger, C.J., Garber, A.F., 2002. Aquaculture escapement, implications and mitigation: the salmonid case study. in: Costa-Pierce, B.A. (Ed.), *Ecological aquaculture: the evolution of the blue revolution*. Blackwell Science Ltd., Oxford, pp. 77-102.
- Brooking, P., Doucette, G., Tinker, S., Whoriskey, F.G., 2006. Sonic tracking of wild cod, *Gadus morhua*, in an inshore region of the Bay of Fundy: a contribution to understanding the impact of cod farming for wild cod and endangered salmon populations. *ICES J. Mar. Sci.* 63, 1364-1371.
- Chittenden, C.M., Rikardsen, A.H., Skilbrei, O.T., Davidsen, J.G., Halttunen, E., Skarðhamar, J., McKinley, R.S., 2011. An effective method for the recapture of escaped farmed salmon. *Aquaculture Environment Interactions* 1: 215 – 224.
- Costello, M.J., 2009. How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proceedings of the Royal Society B: Biological Sciences*. 276, 3385-3394.
- Cramon-Taubadel, N.V., Ling, E.N., Cotter, D., Wilkins, N.P., 2005. Determination of body shape variation in Irish hatchery-reared and wild Atlantic salmon. 66, 1471-1482. *J. Fish Biol.* 66, 1471-1482.
- Crawford, C., 2003. Qualitative risk assessment of the effects of shellfish farming on the environment in Tasmania, Australia Ocean Coast. Manage. 46, 47-58.
- Cross, T.F., Burnell, G., Coughlan, J., Culloty, S., Dillane, E., McGinnity, P., Rogan, E., 2008. Detrimental genetic effects of interactions between reared strains and wild populations of marine and anadromous fish and invertebrate populations. in: Holmer, M., Black, K., Duarte, C.M., Marbà, N., Karakassis, I. (Eds.), *Aquaculture in the ecosystem*. Springer, pp. 117-154.
- Davenport, J., Black, K., Burnell, G., Cross, T., Culloty, S., Ekarante, S., Furness, B., Mulcahy, M., Thetmeyer, H., 2003. *Aquaculture: the ecological issues*. Blackwell Publishing, Oxford.
- Einum, S., Fleming, I.A., 1997. Genetic divergence and interactions in the wild among native, farmed and hybrid Atlantic salmon. *J. Fish Biol.* 50, 634-651.
- Einum, S., Fleming, I.A., 2001. Implications of stocking: ecological interactions between wild and released salmonids. *Nordic Journal of Freshwater Research*. 75, 56-70.
- Eriksson, T., Eriksson, L.O., 1991. Spawning migratory behaviour of coastal-released Baltic salmon (*Salmo salar*). Effects on straying frequency and time of river ascent. *Aquaculture*. 98, 79-87.
- FAO Fisheries and Aquaculture Department, 2009. *FAO yearbook - world fisheries and aquaculture statistics - 2007*. pp. xxiv + 73.
- FAO Fisheries and Aquaculture Department, 2010. *Global datasets, FishStat Plus - Universal software for fishery statistical time series*.
- <http://www.fao.org/fishery/statistics/software/fishstat/en>. Access date: March 22, 2010.
- Fiske, P., Lund, R.A., Hansen, L.P., 2006. Relationships between the frequency of farmed Atlantic salmon, *Salmo salar* L., in wild salmon populations and fish farming activity in Norway, 1989-2004. *ICES J. Mar. Sci.* 63, 1182-1189.
- Fiske, P., Lund, R.A., Østborg, G.M., Fløystad, L., 2001. Escapees of reared salmon in coastal and riverine fisheries in the period 1989-2000. *NINA Oppdragsmelding*. 704, 1-26.

- Fleming, I.A., Einum, S., 1997. Experimental tests of genetic divergence of farmed from wild Atlantic salmon due to domestication. *ICES J. Mar. Sci.* 54, 1051-1063.
- Fleming, I.A., Hindar, K., Mjølnerod, I.B., Jonsson, B., Balstad, T., Lamberg, A., 2000. Lifetime success and interactions of farm salmon invading a native population. *Proceedings of the Royal Society B: Biological Sciences.* 267, 1517-1523.
- Fleming, I.A., Jonsson, B., Gross, M.R., 1994. Phenotypic divergence of sea-ranched, farmed, and wild salmon. *Can. J. Fish. Aquat. Sci.* 51, 2808-2824.
- Ford, J.S., Myers, R.A., 2008. A global assessment of salmon aquaculture impacts on wild salmon, *PLoS Biology.*
- Fosså, J.H., Nordeide, J.T., Salvanes, A.G.V., Smedstad, O., 1994. Impacts of released cod on wild fish populations in Masfjorden, western Norway. *Aquacult. Fish. Manage.* 25 (Suppl.1), 35-48.
- Fraser TWK, Hansen T, Skjaeraasen JE, Mayer I, Sambraus F, Fjellidal PG (2013) The effect of triploidy on the culture performance, deformity prevalence, and heart morphology in Atlantic salmon. *Aquaculture* 416:255-264
- Glover KA, Pertoldi C, Besnier F, Wennevik V, Kent M, Skaala O (2013) Atlantic salmon populations invaded by farmed escapees: quantifying genetic introgression with a Bayesian approach and SNPs. *BMC Genet* 14
- Green DM, Penman DJ, Migaud H, Bron JE, Taggart JB, *et al.* (2012) The Impact of Escaped Farmed Atlantic Salmon (*Salmo salar* L.) on Catch Statistics in Scotland. *PLoS ONE* 7(9): e43560. doi:10.1371/journal.pone.0043560
- Hansen LP, Youngsson AF (2010) Dispersal of large farmed Atlantic salmon, *Salmo salar*, from simulated escapes at fish farms in Norway and Scotland. *Fish Manag Ecol* 17: 28–32
- Hansen T, Karlsen O, Taranger GL, Hemre GI, Holm JC, Kjesbu OS (2001) Growth, gonadal development and spawning time of Atlantic cod (*Gadus morhua*) reared under different photoperiods. *Aquaculture* 203:51-67
- Hansen, L.P., 2006. Migration and survival of farmed Atlantic salmon (*Salmo salar* L.) released from two Norwegian fish farms. *ICES J. Mar. Sci.* 63, 1211-1217.
- Hansen, L.P., Døving, K.B., Jonsson, B., 1987. Migration of farmed Atlantic salmon with and without olfactory sense, released on the Norwegian coast. *J. Fish Biol.* 30, 713-721.
- Hansen, L.P., Jacobsen, J.A., 2003. Origin and migration of wild and escaped farmed Atlantic salmon, *Salmo salar* L., in oceanic areas north of the Faroe Islands. *ICES J. Mar. Sci.* 60, 110-119.
- Hansen, L.P., Jonsson, B., 1991. The effect of timing of Atlantic salmon smolt and post-smolt release on the distribution of adult returns. *Aquaculture.* 98, 61-67.
- Hard, J.J., Berejikian, B.A., Tezak, E.P., Schroder, S.L., Knudsen, C.M., Parker, L.T., 2000. Evidence for morphometric differentiation of wild and captive reared adult coho salmon: a geometric analysis. *Environ. Biol. Fish.* 58: 61–73. *Environ. Biol. Fish.* 58, 61-73.
- Hargrave, B., 2005. Environmental effects of marine finfish aquaculture. Springer, Berlin.
- Heggberget, T.G., Økland, F., Ugedal, O., 1993. Distribution and migratory behaviour of adult wild and farmed Atlantic salmon (*Salmo salar*) during return migration. *Aquaculture.* 118,73-83.
- Heggberget, T.G., Økland, F., and Ugedal, O. 1993. Distribution and migratory behaviour of adult wild and farmed Atlantic salmon (*Salmo salar*) during return migration. *Aquaculture,* 118: 73-83.
- Hindar, K., Fleming, I.A., McGinnity, P., Diserud, O., 2006. Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES J. Mar. Sci.* 63,1234-1247.

- Hislop, J.R.G., and Webb, J.H. 1992. Escaped farmed Atlantic salmon, *Salmo salar* L., feeding in Scottish coastal waters. *Aquaculture and Fishery Management*, 23: 721–723.
- ICES WGNAS, 2010. Incidence of escapee farmed salmon in coastal areas and rivers of the northeast Atlantic.
- Jacobsen, J.A., Hansen, L.P., 2001. Feeding habits of wild and escaped farmed Atlantic salmon, *Salmo salar* L., in the Northeast Atlantic. *ICES J. Mar. Sci.* 58, 916-933.
- Jensen, Ø., Dempster, T., Thorstad, E. B., Uglem, I., and Fredheim, A. 2010. Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. *Aquaculture Environment Interactions*, 1: 71-83.
- Jonsson, B., 1997. A review of ecological and behavioural interactions between cultured and wild Atlantic salmon. *ICES J. Mar. Sci.* 54, 1031-1039.
- Jonsson, B., Jonsson, N., 2004. Factors affecting marine production of Atlantic salmon (*Salmo salar*). *Can. J. Fish. Aquat. Sci.* 61, 2369-2383.
- Jonsson, B., Jonsson, N., 2006. Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. *ICES J. Mar. Sci.* 63, 1162-1181.
- Jonsson, B., Jonsson, N., Hansen, L.P., 1990. Does juvenile experience affect migration and spawning of adult Atlantic salmon? *Behavioral Ecology and Sociobiology*. 26, 225-230.
- Jonsson, N., Hansen, L.P., Jonsson, B., 1993. Migratory behaviour and growth of hatchery-reared post-smolt Atlantic salmon, *Salmo salar* L. *J. Fish Biol.* 42, 435-443.
- Jonsson, N., Hansen, L.P., Jonsson, B., 1994. Juvenile experience influences timing of adult river ascent in Atlantic salmon. *Anim. Behav.* 48, 740-742.
- Jørstad, K.E., van der Meeren, T., Paulsen, O.I., Thomsen, T., Thorsen, A., Svåsand, T., 2008. "Escapes" of eggs from farmed cod spawning in net pens: recruitment to wild stocks. *Rev. Fish. Sci.* 16, 285-295.
- Klemetsen, A., Amundsen, P.A., Dempson, J.B., Jonsson, B., Jonsson, N., O'Connell, M.F., Mortensen, E., 2003. Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): A review of aspects of their life histories. *Ecology of Freshwater Fish*. 12, 1-59.
- Kostow, K.E., 2004. Differences in juvenile phenotypes and survival between hatchery stocks and a natural population provide evidence for modified selection due to captive breeding. *Can. J. Fish. Aquat. Sci.* 61, 577-589.
- Kristiansen, T.S., Ottera, H., Svasand, T., 2000. Size-dependent mortality of juvenile Atlantic cod, estimated from recaptures of released reared cod and tagged wild cod. *J. Fish Biol.* 56,687-712.
- Lacroix, G.L., Knox, D., 2005. Distribution of Atlantic salmon (*Salmo salar*) postsmolts of different origins in the Bay of Fundy and Gulf of Maine and evaluation of factors affecting migration, growth, and survival. *Can. J. Fish. Aquat. Sci.* 62, 1363-1376.
- Leggatt, R., O'Reilly, P., Blanchfield, P.J., McKindsey, C.W., Devlin, R.H., 2009. Pathway of effects of escaped aquaculture organisms or their reproductive material on natural ecosystems in Canada. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2009/XXX.
- Lund, R.A., Økland, F., Hansen, L.P., 1991. Farmed Atlantic salmon (*Salmo salar*) in fisheries and rivers in Norway. *Aquaculture*. 98, 143-150.
- McGinnity, P., Prodöhl, P., Ferguson, A., Hynes, R., Maoiléidigh, N.Ó., Baker, N., Cotter, D., O'Hea, B., Cooke, D., Rogan, G., Taggart, J., Cross, T., 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society B: Biological Sciences*. 270, 2443-2450.

- Meager, J.J., Skjæraasen, J.E., Fernö, A., Karlsen, Ø., Løkkeborg, S., Michalsen, K., Utskot, S.O., 2009. Vertical dynamics and reproductive behaviour of farmed escapee and wild cod (*Gadus morhua*). Mar. Ecol. Prog. Ser. 389, 233-243.
- Moe, H., Dempster, T., Sunde, L.M., Winther, U., Fredheim, A., 2007. Technological solutions and operational measures to prevent escapes of Atlantic cod (*Gadus morhua*) from sea cages. Aquac. Res. 38, 91-99.
- Morton, A., Volpe, J.P., 2002. A description of escaped farmed Atlantic salmon *Salmo salar* captures and their characteristics in one Pacific salmon fishery area in British Columbia, Canada, in 2000. Alaska Fishery Research Bulletin. 9, 102-110.
- Naylor, R., Burke, M., 2005. Aquaculture and ocean resources: raising tigers in the sea. Ann.Rev. Environ. Resour. 30, 185-218.
- Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature. 405, 1017-1024.
- Nørdtvedt, M., Fernø, A., Steingrund, P., Gjørseter, J., 1999. Anti-predator behaviour of hatchery-reared and wild Atlantic cod (*Gadus morhua* L.), and the effect of predator training. in: Howell, B.R., Moksness, E., Svåsand, T. (Eds.), Stock Enhancement and Sea Ranching. Blackwell Science Ltd, pp. 350-362.
- Nordeide, J.T., Salvanes, A.G.V., 1991a. Observations on reared nearly released and wild cod (*Gadus morhua* L.) and their potential predators. ICES Mar. Sci. Symp. 192, 139-146.
- Nordeide, J.T., Salvanes, A.G.V., 1991b. Observations on reared nearly released and wild cod (*Gadus morhua* L.) and their potential predators. ICES Mar. Sci. Symp. 192, 139-146.
- Økland, F., Heggberget, T.G., Jonsson, B., 1995. Migratory behaviour of wild and farmed Atlantic salmon (*Salmo salar*) during spawning. J. Fish Biol. 46, 1-7.
- Olsen, R.E., Skilbrei, O.T. 2010. Feeding preference of recaptured Atlantic salmon, *Salmo salar*, that escaped from fish pens during autumn. Aquaculture Environment Interactions 1: 167 – 174.
- Patterson K., Blanchfield PJ (2013) *Oncorhynchus mykiss* escaped from commercial freshwater aquaculture pens in Lake Huron, Canada. Aquaculture Environment Interactions 4:53-65
- Power, J.H., McCleave, J.D., 1980. Riverine movements of hatchery reared Atlantic salmon (*Salmo salar*) upon return as adults. Environ. Biol. Fish. 5, 3-13.
- Salvanes, A.G.V., Braithwaite, V., 2006. The need to understand the behaviour of fish reared for mariculture or restocking. ICES J. Mar. Sci.
- Serra-Llinares RM, Bjørn PA, Finstad B, Nilsen R, Harbitz A, Berg M, Asplin L (2014) Salmon lice infection on wild salmonids in marine protected areas: an evaluation of the Norwegian 'National Salmon Fjords'. Aquacult Environ Interact 5:1-16
- Skaala Ø, Glover KA, Barlaup BT, Svåsand T, Besnier F, Hansen MM, Borgstrøm R (2012) Performance of farmed, hybrid, and wild Atlantic salmon (*Salmo salar*) families in a natural river environment. Can J Fish Aquat Sci:1-13
- Skilbrei, O. T. 2010b. Adult recaptures of farmed Atlantic salmon post-smolts allowed to escape during summer. Aquaculture Environment Interactions, 1: 147-153.
- Skilbrei, O. T., Holst, J. C., Asplin, L., & Mortensen, S. 2010. Horizontal movements of simulated escaped farmed Atlantic salmon (*Salmo salar* L.) in a western Norwegian fjord. – ICES Journal of Marine Science, 67: 1206-1215.
- Skilbrei, O., Wennevik, V., 2006. The use of catch statistics to monitor the abundance of escaped farmed Atlantic salmon and rainbow trout in the sea. ICES J. Mar. Sci. 63, 1190-1200.

- Skilbrei, O.T. 2010a. Reduced migratory performance of farmed Atlantic salmon post-smolts from a simulated escape during autumn. *Aquaculture Environment Interactions* 1: 117 – 125.
- Skilbrei, O.T. 2012. The importance of escaped farmed rainbow trout (*Oncorhynchus mykiss*) as a vector for the salmon louse (*Lepeophtheirus salmonis*) depends on the hydrological conditions in the fjord. *Hydrobiologia* 6686, 287-297
- Skilbrei, O.T., and Jørgensen, T. 2010. Recapture of cultured salmon following a large-scale escape experiment. *Aquaculture Environment Interactions*, 1: 107-115.
- Skjæraasen, J.E., Mayer, I., Meager, J.J., Rudolfson, G., Karlsen, Ø., T., H., Kleven, O., 2009. Sperm characteristics and competitive ability in farmed and wild cod. *Mar. Ecol. Prog. Ser.* 375, 219-228.
- Solberg MF, Skaala Ø, Nilsen F, Glover KA (2013) Does Domestication Cause Changes in Growth Reaction Norms? A Study of Farmed, Wild and Hybrid Atlantic Salmon Families Exposed to Environmental Stress. *PLoS ONE* 8:e54469
- Soto, D., Arismendi, I., González, J., Sanzana, J., Jara, F., Jara, C., Guzman, E., Lara, A., 2006. Southern Chile, trout and salmon country: Invasion patterns and threats for native species. *Rev. Chil. Hist. Nat.* 79, 97-117.
- Soto, D., Jara, F., and Moreno, C. 2001. Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. *Ecological Applications*, 11: 1750–1762.
- Steingrund, P., Fernø, A., 1997. Feeding behaviour of reared and wild cod and the effect of learning: two strategies of feeding on two-spotted gobies. *J. Fish Biol.* 51, 334-348.
- Svåsand, T, Skilbrei, O.T., van der Meeren, G.I., and Holm, M. (1998) Review of morphological and behavioural differences between reared and wild individuals: Implications for sea-ranching of Atlantic salmon, *Salmo salar* L., Atlantic cod, *Gadus morhua* L., and European lobster, *Homarus gammarus* L. *Fisheries management and Ecology* 5, 473-490.
- Thorpe, J.E., 2004. Life history responses of fishes to culture. *J. Fish Biol.* 65 (suppl. A), 263-285.
- Thorstad, E.B., Heggberget, T.G., Økland, F., 1998. Migratory behaviour of adult wild and escaped farmed Atlantic salmon, *Salmo salar* L., before, during and after spawning in a Norwegian river. *Aquac. Res.* 29: 419–428. *Aquac. Res.* 29, 419-428.
- Thorstad, E.B., Fleming, I.A., McGinnity, P., Soto, D., Wennevik, V., Whoriskey, F., 2008. Incidence and impacts of escaped farmed Atlantic salmon *Salmo salar* in nature. *NINA Special Report* 36: pp. 110.
- Weir, L.K., Fleming, I.A., 2006. Behavioural interactions between farm and wild salmon: potential for effects on wild populations. in: *Fisheries and Oceans Canada (Ed.), A scientific review of the potential environmental effects of aquaculture in aquatic ecosystems. Canadian Technical Report of Fisheries and Aquatic Sciences* 2450, Vol V, pp. 1-29.
- Weir, L.K., Hutchings, J.A., Fleming, I.A., Einum, S., 2004. Dominance relationships and behavioural correlates of individual spawning success in farmed and wild male Atlantic salmon, *Salmo salar*. *J. Anim. Ecol.* 73, 1069-1079.
- Whoriskey, F., Brooking, P., Doucette, G., Tinker, S., Carr, J., 2006. Movements and fate of sonically tagged farmed Atlantic salmon released in Cobscook Bay, Maine, USA. *ICES J. Mar. Sci.* 63, 1218-1223.
- Wroblewski, J.S., Smedbol, R.K., Taggart, C.T., Goddard, S.V., 1996. Movements of farmed and wild Atlantic cod (*Gadus morhua*) released in Trinity Bay, Newfoundland. *Mar. Biol.* 124, 619-627.
- Youngson, A.F., Dosdat, A., Saroglia, M., Jordan, W.C., 2001. Genetic interactions between marine finfish species in European aquaculture and wild conspecifics. *J. Appl. Ichthyol.* 17, 153-162.

4.2 Nutrient and organic matter waste products

4.2.1 Bivalve biodeposition and nutrient fluxes (Chris McKindsey, Canada)

There are several recent reviews of the environmental interactions of bivalve culture. These include one on infaunal bivalves and oysters in estuaries (Dumbauld *et al.* 2009), one on oyster culture (Forrest *et al.* 2009), and one on benthic effects mussel culture (McKindsey *et al.* 2011). There are also several reports on the subject (Anderson *et al.* 2006, Cranford *et al.* 2006, McKindsey *et al.* 2006, Keeley *et al.* 2009, McKindsey 2011). This section draws heavily on these past reviews, as well as using more recent information, when available and appropriate.

Bivalve culture has a number of main direct effects (Figure 4). As filter-feeders, the first is the filtration of seston from the water column. Part of what is thus captured is excreted as faeces and another portion is sorted out and rejected as pseudofaeces without being ingested. Collectively, these are known as biodeposits and may enrich benthic conditions. Third, there is the addition of considerable physical structure to environments in which bivalves are farmed. This structure includes the various ropes, nets, shelving or racks, buoys, and netting that are used to grow the farmed bivalves but also the bivalves themselves, which are often important foundation species when growing under natural conditions. In addition, nutrients fluxes may be modified by bivalve aquaculture. The first and third issues are discussed under other sections. Here, the major issues associated with organic loading to the benthos and related and other nutrient fluxes are outlined.

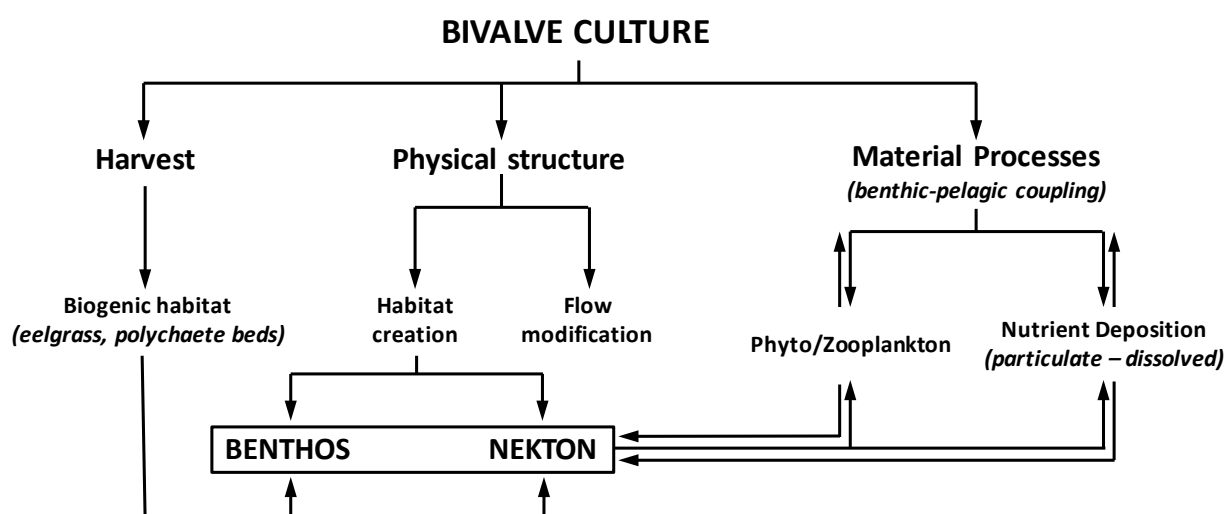


Figure 4. Conceptual diagram of major ecological interactions between bivalve culture and the ecosystem (modified from Dumbauld 2009).

Biodeposits, when released from bivalves grown in suspended or off-bottom culture, settle relatively quickly to the bottom, where they may greatly increase organic loading within and immediately around farm sites (Dame 1996, Newell 2004). Other than the farmed biomass, the degree to which biodeposits accumulate in the vicinity of farms is a function of the rate of biodeposit production, initial dispersal (i.e., the transport of biodeposits in the water column due to hydrodynamic processes until their first contact with the seabed), the redistribution of biodeposits on the sediment surface via creep, saltation and/or resuspension (i.e., erosion), and the rate of biodeposit decay (Giles 2009). Biodeposit production and settlement rates varies with bi-

valve size, species, and diet and is quite variable over short time scales (e.g., Weise *et al.* 2009) but generally fall in the range of about 0.25 to 3 cm sec⁻¹ (McKindsey *et al.* 2011).

Biodeposits are typically rich in carbon and nitrogen (Kautsky & Evans 1987) but this depends on diet (Miller *et al.* 2002), which may vary greatly both spatially and temporally (Bayne *et al.* 1993). Numerous studies have shown that increased biodeposition related to bivalve culture impacts benthic sediment geochemistry (Dahlbäck & Gunnarsson 1981, Mattsson & Lindén 1983). In short, organic matter is decomposed by microbes follow a sequence of oxidant reductions (O₂, NO₃⁻, MnO₂, FeO₂H, SO₄²⁻, HCO₃⁻) and may locally increase oxygen demand. When the decay of such organic substrates consumes oxygen at a rate that is greater than at which it is replaced by water exchange, anoxic conditions that induce sulphate reduction near the surface may ensue. Dissolved sulfides (HS⁻, H₂S, S₂⁻) produced may be transformed into metal sulfides such as iron monosulfides (FeS), greigite (Fe₃S₄) and ultimately pyrite (FeS₂) and are highly toxic, especially undissociated hydrogen sulfides (H₂S). Thus sediment redox potential and sulphide levels have been used to detect the effects of high organic loading under suspended bivalve farms (Hargrave *et al.* 2008, Cranford *et al.* 2009, Keeley *et al.* 2009).

Free sulphides, such as H₂S, may enter the cells living in such sediments by passive diffusion and thus impact benthic communities. Indeed, many studies have shown that infaunal communities subjected to organic loading from bivalve culture respond in a manner that is consistent with the Pearson and Rosenberg (1978) model of organic enrichment. In short, as the level of organic input increases, typical soft sediment communities dominated by large filter-feeders are replaced by increased numbers of smaller, deposit-feeding opportunistic organisms, starting with small polychaetes (e.g., *Capitella* spp.) and then shifting to nematodes. Ultimately, benthic conditions may become anoxic and dominated by mats of the bacteria *Beggiatoa* spp. Biomass and species richness may increase with limited organic loading whereas abundance may increase with moderate loading as smaller species come to dominate. At great loading rates, all standard measures of benthic condition are reduced as bottom sediments become hypoxic or even anoxic. However, as pointed out by Keeley *et al.* (2009) the impacts of suspended bivalve culture on benthic infaunal communities are typically limited in magnitude except for under extreme conditions (poor flushing or exceedingly great stocking densities). Responsible husbandry practices may be used to limit these impacts.

How such effects are transferred up the food-chain to impact fisheries species is not clear. Although changes in benthic infaunal communities due to bivalve culture may allow juvenile fishes and other organisms to profit from the abundance of small in-fauna often observed in culture sites (Tenore & Dunstan 1973), it is not clear if this actually occurs, although there is sometimes increased abundances of such organisms inside of culture sites relative to areas outside of culture sites.

Seagrasses may be impacted by bivalve culture in a variety of ways. Organic loading related to bivalve farming may impact seagrasses, either by direct smothering or indirectly via degradation of benthic conditions (e.g., increased sulphide levels). Seagrasses may also be impacted by shading (from suspended or on- and off-bottom structures, anti-predator netting used for infaunal clam culture). In addition, seagrasses may be impacted by harvesting and maintenance activities (e.g., walking through beds or harvesting from beds) or modification of benthic sediment structure to improve husbandry conditions. Note that, at greater spatial scales, filtration related

to bivalve culture may increase water clarity and thus have positive impacts on seagrass beds. Given the importance of seagrasses as nursery habitats for a variety of fisheries species and providing a variety of ecosystem services globally, impacts to fisheries species due to changes in the condition of seagrass beds due to bivalve culture should be considered. To our knowledge, holistic studies on the impact of multiple effects from bivalve farming on seagrasses (e.g., shading and increasing water clarity) and related fisheries species are lacking. Such scale-dependent processes must be better understood to place the impact of bivalve culture in an ecosystem context.

Another form of organic loading related particularly to suspended mussel culture is the fall-off of farmed mussels and associated epifauna. This constitutes an important increase “benthic” biomass that is available for benthic macrofaunal predators. Accordingly, there is often an increased abundance of such organisms within farm sites relative to areas outside of farms. In some cases, such as crabs in Spanish rias, it appears that these predators shift their diet towards species that are associated with bivalve culture. More commonly, the effect of the addition of such prey is confounded by the addition of structure in the form of anchors for longlines, which also serves as habitat, and thus ascribing cause and effect is not easy. Again, it is not clear what this impact has on the fitness of such species, including those that are targeted by fisheries.

Bivalve aquaculture may impact oxygen and nutrient levels directly through respiration and excretion (by the bivalves themselves and the organisms associated with them and the grow-out structures) and by modifying benthic conditions that, in turn, impact benthic respiration and nutrient exchanges. As most bivalve aquaculture is done in coastal areas, where benthic oxygen demand may be great (Borsuk *et al.* 2001, Fulweiler *et al.* 2010), and nutrient regeneration in shallow waters is largely controlled by benthic remineralization of nutrients in the water (Kaspar *et al.* 1985, Mazouni *et al.* 1996), the importance of bivalve culture to local oxygen and nutrient levels may thus be considerable— at least in the vicinity of farms.

In addition to the farmed bivalves themselves, organic matter that accumulates within the culture structure matrix and biofouling also contribute to respiration, thus impacting oxygen levels locally, and nutrient fluxes due to culture structures (Mazouni *et al.* 2001, Nizzoli *et al.* 2006). Biodeposition from farmed bivalves to the bottom increases oxygen consumption and nutrient fluxes at the water-sediment interface (Baudinet *et al.* 1990, Richard *et al.* 2007). Benthic fluxes of ammonium, nitrate/nitrite, phosphate, and silicate fluxes are typically greater within culture sites than areas without bivalve culture (Giles *et al.* 2006, Carlsson *et al.* 2009, Alonso-Pérez *et al.* 2010). It is not clear what effect this may have on primary producers, but it may lead to cascading effects that are much greater than simple shifts in nutrient levels (Hatcher *et al.* 1994).

References

- Alonso-Pérez F, Ysebaert T, Castro CG (2010) Effects of suspended mussel culture on benthic-pelagic coupling in a coastal upwelling system (Ría de Vigo, NW Iberian Peninsula). *J Exp Mar Biol Ecol* 382:96-107
- Anderson MR, Cranford P, McKindsey CW, Strain P, Hargrave BT, Li WKW, Harrison WG (2006) Cumulative and far-field fish habitat effects. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/037, vi + 30 p. http://www.dfo-mpo.gc.ca/csas-sccs/publications/resdocs-docrech/2006/2006_037-eng.htm

- Baudinet D, Alliot E, Berland B, Grenz C, Plante-Cuny M, Plante R, Salen-Picard C (1990) Incidence of mussel culture on biogeochemical fluxes at the sediment-water interface. *Hydrobiologia* 207:187-196
- Bayne BL, Iglesias JIP, Hawkins AJS, Navarro E, Heral M, Deslous-Paoli JM (1993) Feeding behaviour of the mussel, *Mytilus edulis*: responses to variations in quantity and organic content of the seston. *J Mar Biol Ass U K* 73:813-829
- Borsuk ME, Higdon D, Stow CA, Reckhow KH (2001) A Bayesian hierarchical model to predict benthic oxygen demand from organic matter loading in estuaries and coastal zones. *Ecol Model* 143:165-181
- Carlsson MS, Holmer M, Petersen JK (2009) Seasonal and spatial variations of benthic impacts of mussel longline farming in a eutrophic Danish fjord, Limfjorden. *J Shellfish Res* 28:791-801
- Cranford P, Anderson R, Archambault P, Balch T, Bates S, Bugden G, Callier MD, Carver C, Comeau L, Hargrave B, Harrison G, Horne E, Kepay PE, Li WKW, Mallet A, Ouellette M, Strain P (2006) Indicators and thresholds for use in assessing shellfish aquaculture impacts on fish habitat. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/034, viii + 116 p.
- Cranford PJ, Hargrave BT, Doucette LI (2009) Benthic organic enrichment from suspended mussel (*Mytilus edulis*) culture in Prince Edward Island, Canada. *Aquaculture* 292:189-196
- Dahlbäck B, Gunnarsson LÅH (1981) Sedimentation and sulfate reduction under a mussel culture. *Mar Biol* 63:269-275
- Dame RF (1996) Ecology of marine bivalves: an ecosystem approach. CRC Press, Boca Raton
- Dumbauld BR, Ruesink JL, Rumrill SS (2009) The ecological role of bivalve shellfish aquaculture in the estuarine environment: a review with application to oyster and clam culture in West Coast (USA) estuaries. *Aquaculture* 290:196-223
- Forrest BM, Keeley NB, Hopkins GA, Webb SC, Clement DM (2009) Bivalve aquaculture in estuaries: Review and synthesis of oyster cultivation effects. *Aquaculture* 298:1-15
- Fulweiler R, Nixon S, Buckley B (2010) Spatial and temporal variability of benthic oxygen demand and nutrient regeneration in an anthropogenically impacted New England estuary. *Estuar Coasts* 33:1377-1390
- Giles H (2009) Modelling the dispersal of biodeposits from mussel farms: The importance of simulating biodeposit erosion and decay. *Aquaculture* 291:168-178
- Giles H, Pilditch CA, Bell DG (2006) Sedimentation from mussel (*Perna canaliculus*) culture in the Firth of Thames, New Zealand: Impacts on sediment oxygen and nutrient fluxes. *Aquaculture* 261:125-140
- Hargrave BT, Doucette LI, Cranford PJ, Law BA, Milligan TG (2008) Influence of mussel aquaculture on sediment organic enrichment in a nutrient-rich coastal embayment. *Mar Ecol Prog Ser* 365:137-149
- Hatcher A, Grant J, Schofield B (1994) Effects of suspended mussel culture (*Mytilus* spp.) on sedimentation, benthic respiration and sediment nutrient dynamics in a coastal bay. *Mar Ecol Prog Ser* 115:219-235
- Kaspar HF, Gillespie P, Boyer LF, Mackenzie AL (1985) Effects of mussel aquaculture on the nitrogen cycle of benthic communities in Kenepuru Sound, Marlborough Sound, New Zealand. *Mar Biol* 85:127-136
- Kautsky N, Evans S (1987) Role of biodeposition by *Mytilus edulis* in the circulation of matter and nutrients in a Baltic coastal ecosystem. *Mar Ecol Prog Ser* 38:201-212
- Keeley N, Forrest B, Hopkins G, Gillespie P, Knight B, Webb S, Clement D, Gardner J (2009) Review of the ecological effects of farming shellfish and other non-fish species in New Zealand. Cawthron Report No. 1476, Cawthron Institute, 174 + xiv p.

- Mattsson J, Lindén O (1983) Benthic macrofauna succession under mussels, *Mytilus edulis* L. (Bivalvia), cultured on hanging long-lines. *Sarsia* 68:97-102
- Mazouni N, Gaertner JC, Deslous-Paoli JM (2001) Composition of biofouling communities on suspended oyster cultures: an in situ study of their interactions with the water column. *Mar Ecol Prog Ser* 214:93-102
- Mazouni N, Gaertner JC, Deslous-Paoli JM, Landrein S, Geringer d'Oedenberg M (1996) Nutrient and oxygen exchanges at the water-sediment interface in a shellfish farming lagoon (Thau, France). *J Exp Mar Biol Ecol* 205:91-113
- McKindsey CW (2011) Aquaculture-related physical alterations of habitat structure as ecosystem stressors. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/024, viii + 154 p. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2010/2010_024-eng.html
- McKindsey CW, Anderson MR, Barnes P, Courtenay S, Landry T, Skinner M (2006) Effects of shellfish aquaculture on fish habitat. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/011, viii + 84 p. http://www.dfo-mpo.gc.ca/csas-sccs/publications/resdocs-docrech/2006/2006_011-eng.htm
- McKindsey CW, Archambault P, Callier MD, Olivier F (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Can J Zool* 89:622-646
- Miller DC, Norkko A, Pilditch CA (2002) Influence of diet on dispersal of horse mussel *Atrina zelandica* biodeposits. *Mar Ecol Prog Ser* 242:153-167
- Newell RIE (2004) Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. *J Shellfish Res* 23:51-61
- Nizzoli D, Bartoli M, Viaroli P (2006) Nitrogen and phosphorous budgets during a farming cycle of the Manila clam *Ruditapes philippinarum*: An in situ experiment. *Aquaculture* 261:98-108
- Pearson TH, Rosenberg R (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr Mar Biol Ann Rev* 16:229-311
- Richard M, Archambault P, Thouzeau G, McKindsey CW, Desrosiers G (2007) Influence of suspended scallop cages and mussel lines on pelagic and benthic biogeochemical fluxes in Havre-aux-Maisons Lagoon, Îles-de-la-Madeleine (Quebec, Canada). *Can J Fish Aquat Sci* 64:1491-1505
- Tenore KR, Dunstan WM (1973) Comparison of feeding and biodeposition of three bivalves at different food levels *Mar Biol* 21:190-195
- Weise AM, Cromey CJ, Callier MD, Archambault P, Chamberlain J, McKindsey CW (2009) Shellfish-DEPOMOD: Modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. *Aquaculture* 288:239-253

4.2.2 Finfish excretion, faeces and waste feed (Raymond Bannister, Norway)

The intensive farming of fin-fish in open net-pens leads to the release of organic and inorganic effluents (i.e. carbon, nitrogen and phosphorus) in the form of waste feed, faeces and metabolic by-products to the surrounding aquatic marine environments (Holmer *et al.* 2005; Strain & Hargrave 2005). Accumulation of these effluents into the marine system can negatively impact the ecosystem by contributing to eutrophication of pelagic systems, fertilization of benthic macrophytes in the euphotic zone, and organic enrichment of benthic systems (Strain and Hargrave 2005). However, the degree of enrichment of the environment is dependent on a number of factors including, the size of the farm (i.e. the biomass of fish), the ambient environmental

conditions (i.e. hydrodynamics, water depth, wave exposure, topography and substrate type), the husbandry practices at individual fish farms (Holmer *et al.* 2005) and also the biophysical and biochemical composition of the waste streams (Reid *et al.* 2009).

4.2.2.1 Benthic effects

Soft sediment ecosystems: Knowledge on the environmental effects of particulate organic effluents from fin-fish aquaculture on the functioning of benthic ecosystems have been established for fish farms located over shallow soft sediment ecosystems for a number of different fish species (i.e. Atlantic salmon, sea bream, sea bass, yellow tail king fish). Numerous studies have investigated benthic impacts of fish farming on soft sediment shallow water benthic systems, demonstrating that intensive fish farming modifies biogeochemical processes (Holmer and Kristensen 1992; Holmer and Frederiksen 2007; Norði *et al.* 2011). Remineralisation of the highly labile organic waste (i.e. fish feed and faeces) results in increased sediment oxygen demand and altered metabolic pathways, and a shift from aerobic (i.e. heterotrophic respiration) to anaerobic (i.e. sulfate reduction and methanogenesis) microbial degradation (Holmer and Kristiansen 1992; Holmer *et al.* 2003; Valdemarsen *et al.* 2009). Excessive organic enrichment can thus lead to highly modified sediment conditions (Valdemarsen *et al.* 2012), impacting the structure and biomass of faunal communities (Kutti *et al.* 2007b; Hargrave *et al.* 2008; Valdemarsen *et al.* 2010).

However, in addition to shallow water soft sediment ecosystems, fish farming operations can also impact deep (> 100m) soft sediment ecosystems. For example, in Norway, there is a push by the industry to move fish farming operations to deeper locations as well as to more dynamic offshore locations to facilitate the dispersion of organic material from open net pens to minimise gross organic enrichment of the seabed. However, recent evidence demonstrates that moving fish farms to just deeper localities is not the sole factor required to minimise gross enrichment of benthic systems. At deep localities, fish farming effluents can be traced into the wider environment and into benthic food webs (up to at least 1 km from the farming site; Kutti *et al.* 2007a; Olsen *et al.* 2012). At low deposition levels, organic enrichment of deep water benthic sediments (220m deep) stimulates secondary production (up to 500 m from the farming location), resulting in shifts in benthic faunal community structure (Kutti *et al.* 2007b; Kutti 2008; Bannister *et al.* 2014). However, at locations where excessive loading of organic effluents are prevalent, functioning of deep soft sediment systems (200m) is heavily impacted. Valdemarsen *et al.* (2012), demonstrated that moving fish farms to deep fjord localities will lead to grossly anoxic conditions, where both faunal and microbial functioning ceases, resulting in dramatic changes to biogeochemical processes. In contrast, fish farming in more dynamic locations with moderate to high current velocities such as those experienced with off-shore aquaculture can minimize organic enrichment and changes in the structure of benthic faunal communities (Moraitis *et al.* 2013).

Hard bottom and other benthic ecosystems: Scientific knowledge of the ecological impacts of organic enrichment from fin-fish aquaculture have been established from soft sediment ecosystems, however, knowledge on the effects of organic enrichment on other ecosystems are scarce in comparison. With aquaculture moving away from traditional shallow sheltered farming locations (i.e. those characteristic for soft sediment systems) to modern dynamic and offshore farming locations (i.e. those characteristic for featuring mixed and hard bottom habitats) the move to increase our understanding of benthic ecological impacts have not followed suit. The effects of

organic and inorganic enrichment to benthic habitats composed of hard and mixed bottom habitats are poorly studied. A recent study Hansen *et al.* (2012) demonstrated that the community structure of macrofaunal communities on hard bottom substrates shifts from a highly diverse community to a community dominated by opportunistic polychaetes (i.e. *Ophryotrocha spp.* and *Vigorniella spp.*), this was further characterised by Eikje (2013), with the development of the opportunistic community to be correlated to an increase in organic enrichment of the hard bottom benthic system. This limited knowledge highlights the urgency to increase our basic knowledge regarding the assimilative capacity and sensitivity of hard and mixed bottom habitats and the tolerances of associated biota (i.e. flora and fauna) to inorganic and organic effluents under contrasting hydrodynamic settings.

To a lesser extent, there are studies that have investigated the effects of intensive fish farming to other habitats and biota including, maerl beds (Hall-Spencer *et al.* 2006; Sanz-Lazaro *et al.* 2011; Aquado-Giménez and Ruiz-Fernández 2012), coral reefs (Bongiorni *et al.* 2003; Villanueva *et al.* 2006), seaweeds and seagrass beds (Worm and Sommer 2000; Diaz-Almela *et al.* 2008; Duarte *et al.* 2008), megafaunal communities (Wilding *et al.* 2012) and pelagic and demersal fish (Tuya *et al.* 2006; Fernandez Jover *et al.* 2007, 2011a; Dempster *et al.* 2011). A general consensus of these studies is that if the assimilative capacities of these environments are exceeded, then impacts on individual species, habitats, and ecosystems will be pronounced.

4.2.2.2 Pelagic effects

One of the main negative impacts on the water column from fin-fish aquaculture is the potential for elevated nutrient concentrations (Wu *et al.* 1994; Pitta *et al.*, 2006; Verdegem 2013). The buildup of dissolved nutrients in pelagic systems from aquaculture has been suggested as a precursor to eutrophication. Changes in the concentration of nutrients in a water body experiencing poor renewal of water could lead to stimulate phytoplankton growth and plankton blooms (Gowen *et al.* 1992; Pedersen and Borum 1996; Bricker *et al.* 2003), subsequently, reducing dissolved oxygen levels and leading to eutrophication. Changes in phytoplankton communities could also occur, however, from limited scientific knowledge suggests there is no relationship between fish farming nutrient releases and changes in the structure and functioning of pelagic ecosystems (Skejić *et al.* 2010). Although with increasing farming size and the multiple use of the coastal systems, the occurrences of harmful algal blooms could also be prevalent, however direct causal relationships between fin-fish aquaculture and harmful blooms are yet to be established (Tett and Edwards 2002; Forrest *et al.* 2007). In addition, elevated nutrient levels from fish farming activities have the potential to change the structure of seaweed communities by stimulating growth of annual, rapidly growing species that out-compete perennial habitat-building species. Thus, leading to shifts from highly diverse macroalgal communities dominated by perennial brown algae to low diversity communities dominated by opportunists and annual species (Rueness & Fredriksen 1991; Pihl *et al.* 1999; Worm & Sommer 2000; Krause-Jensen *et al.* 2007).

References

- Aquado-Giménez F, Ruiz-Fernández JM (2012) Influence of an experimental fish farm on the spatio-temporal dynamic of a Mediterranean maerl algae community. *Mar Environ Res* 74:47-55.
- Bannister RJ, Valdemarsen TB, Hansen PK, Holmer M, Ervik A. (2014) Changes in benthic sediment conditions under an Atlantic salmon farm at a deep, well-flushed coastal site. *Aquaculture Environment Interactions* 5:29-47

- Bongiorni L, Shafir S, Rinkevich B (2003) Effects of particulate matter released by a fish farm (Eilat, Red Sea) on survival and growth of *Stylophora pistillata* coral nubbins. *Mar Pol Bull* 46:1120-1124.
- Bricker SB, Ferreira JG, Simas T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling* 169:39
- Dempster T, Sanchez-Jerez P, Fernandez-Jover D, *et al.* (2011) Proxy measures of fitness suggest coastal fish farms can act as population sources and not ecological traps for wild gadoid fish. *PlosOne* 6:1-9.
- Diaz-Almela E, Marba N, Alvarez E, *et al.* (2008) Benthic input rates predict seagrass (*Posidonia oceanica*) fish farm induced decline. *Mar Pol Bull* 56:1332-1342.
- Duarte CM, Frederiksen M, Grau A, *et al.* (2008) Effects of fish farm waste on *Posidonia oceanica* meadows; Synthesis and provision of monitoring and management tools. *Mar Pol Bull* 56: 1618-1629.
- Eikje EM (2013) Benthic impacts of fish-farm waste on hard bottom habitats, the ecology of opportunistic epifauna polychaetes. *Masters Thesis, University of Bergen, Norway*. Pp 61.
- Fernandez-Jover D, Lopez-Jimenez JA, Sanchez-Jerez P, *et al.* (2007) Changes in body condition and fatty acid composition of wild Mediterranean horse mackerel (*Trachurus mediterraneus*, Steindachner, 1868) associated to sea-cage fish farms. *Mar. Environ. Res.* 63:1-18.
- Fernandez-Jover D, Martinez-Rubio L, Sanchez-Jerez P, *et al.* (2011a) Waste feed from coastal fish farms: A trophic subsidy with compositional side effects for wild gadoids. *Estuar Coast Shel Sci*, 91:559-568.
- Forrest B, Keeley N, Gillespie P, Hopkins G, Knight B, Govier D. 2007. Review of the ecological effects of marine finfish aquaculture: final report. Prepared for Ministry of Fisheries. *Cawthron Report No. 1285*. 71p.
- Gowen RJ, Tett P, Jones KJ. 1992. Predicting marine eutrophication: the yield of chlorophyll from nitrogen in Scottish coastal waters. *Marine Ecology Progress Series* 85:153-61
- Hall- Spencer J, White N, Gillespie E, *et al.* (2006) Impact of fish farms on maerl beds in strongly tidal areas. *Mar Ecol Prog Ser* 326:1-9.
- Hansen PK, Bannister RJ, Husa V (2012) Discharges from fin-fish aquaculture: Effects on shallow and deep-water hard bottom localities. Ministry of Fisheries and Coastal Affairs report. 30pp (in Norwegian)
- Hargrave BT, Holmer M, Newcombe CP. (2008.) Towards a classification of organic enrichment in marine sediments based on biogeochemical indicators. *Mar Pol Bull* 56:810-824.
- Holmer M, Kristensen E. (1992) Impact of marine fish cage farming on metabolism and sulfate reduction of underlying sediments. *Mar. Ecol. Prog. Ser.* 80:191-201.
- Holmer M, Duarte CM, Heilskov A, *et al.* (2003) Biogeochemical conditions in sediments enriched by organic matter from net-pen fish farms in Bolinao area, Philippines. *Mar Pol Bull* 46:1470-1479.
- Holmer M, Wildish D, Hargrave B (2005) Water Pollution Environmental effects of marine finfish aquaculture. In: *Handbook of Environmental Chemistry, Volume 5*. Editor: Hargrave BT. Berlin Heidelberg: Springer 2005, pages 181-206.
- Holmer M, Frederiksen M (2007). Stimulation of sulfate reduction rates in Mediterranean fish farm sediments. *Biochemistry* 85:169-185.
- Kutti T, Ervik A, Hansen PK (2007a) Effects of organic effluents from a salmon farm on a fjord system. I. Vertical export and dispersal processes. *Aquaculture* 262:367-381
- Kutti T, Hansen PK, Ervik A, *et al.* (2007 b) Effects of organic effluents from a salmon farm on a fjord system. II. Temporal and spatial patterns in infauna community composition. *Aquaculture* 262:355-366.

- Kutti T (2008) Regional impact of organic loading from a salmonid farm – dispersal, sedimentation rates and benthic fauna response. PHD Thesis, University of Bergen.
- Norði GÁ, Glud RN, Gaard E, *et al.* (2011) Environmental impacts of coastal fish farming: carbon and nitrogen budgets for trout farming in Kaldbaksförður (Faroe Islands). *Mar Ecol Prog Ser* 431:223-241.
- Olsen HA, Bøe R, Totland O, *et al.* (2009) Bunnforhold og kamskjellforekomster – kartlegging av to områder i Froan. Geological Survey of Norway, Report no 2009.044. pp 43.
- Pedersen MF, Borum J. 1996. Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae. *Marine Ecology Progress Series* 142:261–72.
- Pihl L, Svenson A, Moksnes PO, Wennehage H. 1999. Distribution of green algal mats throughout shallow soft bottoms of the Swedish Skagerrak archipelago in relation to nutrient sources and wave exposure. *Journal of Sea Research* 41:281–95
- Pitta P, Apostolaki ET, Tsagaraki T, Tsapakakis M, Karakassis I. 2006. Fish farming effects on the chemical and microbiological variables of the water column: A spatio-temporal study along the Mediterranean Sea. *Hydrobiologia* 563:99–108.
- Reid GK, Liutkus M, Robinson SMC, Chopin TR, Blair T, Lander T, Mullen J, Page F, Moccia RD (2009) A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. *Aquaculture Research* 39:1-17
- Rueness J, Fredriksen S. 1991. An assessment of possible pollution effects on the benthic algae of the outer Oslofjord, Norway. *Oebalia* 17:223–35.
- Sanz-Lazaro C, Belando MD, Marin-Guirao L, *et al.* (2011) Relationship between sedimentation rates and benthic impact on Maerl beds derived from fish farming in the Mediterranean. *Mar Environ Res* 71:22-30.
- Skejić S, Marasović I, Vidjak O, Kušpilić G, Gladan Ž N, Šestanović S, Bojanić N (2010) Effects of cage fish farming on phytoplankton community structure, biomass and primary production in an aquaculture area in the middle Adriatic Sea. *Aquaculture Research* 42:1393-1405
- Strain PM, Hargrave BT (2005) Salmon Aquaculture, Nutrient Fluxes and Ecosystem processes in Southwestern New Brunswick. In: *Handbook of Environmental Chemistry, Volume 5*. Editor: Hargrave BT. Berlin Heidelberg: Springer 2005, pages 29-57.
- Tett P and Edwards V (2002) Review of harmful algal blooms in Scottish coastal waters. School of Life Sciences, Napier University, Edinburgh. 120p.
- Tuya F, Sanchez-Jerez P, Dempster T, *et al.* (2006) Changes in demersal wild fish aggregations beneath a sea-cage fish farm after the cessation of farming. *Jof Fish Biol* 69:682-697.
- Valdemarsen TB, Kristensen E, Holmer M (2009) Metabolic threshold and sulfide-buffering in diffusion controlled marine sediments impacted by continuous organic enrichment. *Biogeochemistry* 95:335-353.
- Valdemarsen TB, Kristensen E, Holmer M (2010) Sulfur, carbon and nitrogen cycling in faunated marine sediments impacted by repeated organic enrichment. *Mar Ecol Prog Ser* 400:37-53.
- Valdemarsen TB, Bannister RJ, Hansen PK, *et al.* (2012) Biogeochemical malfunctioning in sediments beneath a Norwegian deep-water fish farm. *Environ Pol* 170:15-25.
- Villanueva RD, Yap HT, Montano MNE. 2006. Intensive fish farming in the Philippines is detrimental to the coral reef-building coral *Pocillopora damicornis*. *Marine Ecology Progress Series* 316: 165-174.
- Verdegem MCJ (2013) Nutrient discharge from aquaculture operations in function of system design and production environment. *Aquaculture reviews* 5:158-171

- Wilding TA, Cromey CJ, Nickell TD, *et al.* (2012) Salmon farm impact on muddy-sediment megabenthic assemblages on the west coast of Scotland. *Aqua Environ Interact* 2:145-156.
- Worm B, Sommer U (2000) Rapid direct and indirect effects of a single nutrient pulse in a seaweed-epiphyte grazer system. *Mar Ecol Prog Ser* 200:283-288
- Wu RSS, Lam KS, MacKay DW, Lau TC, Yam V 1994. Impact of marine fish farming on water quality and bottom sediment: a case study in the sub-tropical environment. *Marine Environmental Research* 38: 115-145.

4.3. Addition of physical structure by bivalve mariculture (Chris Mckindsey, Canada)

Given the, at times, large amount of physical structure that is added to the environment in bivalve culture, this may provide habitat for a variety of organisms, at times greater than that of the cultured bivalves. Although these are not commonly fisheries species (other than second set of mussels and oysters), these organisms may provide appropriate nourishment for mobile fisheries species, such as lobster or crab, or else provide habitat for species that may serve as food for such species. Indeed, many studies have shown that the abundance of many types of fish and macroinvertebrates is greater within culture sites than outside of them. Thus, in some ways, bivalve culture installations may act akin to artificial reefs. However, how such changes impact fisheries and other species is largely unknown.

The physical structure associated with bivalve culture may also impact currents locally and thus benthic sediment conditions. This seems to be particularly true for off-bottom rack culture and bouchot mussel culture. Both accretion and erosion may occur and have significant effects on sediment conditions locally. This has been shown to impact benthic communities in a number of systems (Forrest *et al.* 2009, McKindsey *et al.* 2011). Again, how this impacts fisheries and other species is unknown.

References

- Forrest BM, Keeley NB, Hopkins GA, Webb SC, Clement DM (2009) Bivalve aquaculture in estuaries: Review and synthesis of oyster cultivation effects. *Aquaculture* 298:1-15
- McKindsey CW, Archambault P, Callier MD, Olivier F (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Can J Zool* 89:622-646

4.4 Release of antibiotics and other pharmaceuticals (Dave Jackson, Ireland; Karin Kroon Boxaspen, Norway)

Romero *et al.* (2012) have produced a very detailed review of the use of antibiotics in aquaculture. This is probably the most up to date and comprehensive source of information on antibiotic use. In addition to setting out facts in terms of rates of use of antibiotics, potential consequences of improper use and side effects on target organisms it also details advances in alternative strategies for disease management which reduce reliance on antibiotics for pathogen control.

The development of aquaculture on a global scale led to increased use of antibiotics for disease control. Defoirdt *et al.* (2011) estimated that in 1994 circa 500–600 metric tonnes of antibiotic were used in the farming of shrimp in Thailand alone. Antibiotic use in aquaculture has led to the development of resistance. Three mechanisms of acquired resistance development in bacteria are known to occur in the aquatic envi-

ronment: Transformation by uptake of foreign DNA from the environment, Transduction through infection with viral DNA by bacteriophages and Conjugation (plasmid transfer). Both Transduction and Conjugation can give rise to the development of multi-drug resistance. Numerous studies in salmon and trout have documented resistance development in *Aeromonas* spp. Environmental effects are less clear but Oxy-tetracycline resistance has been detected in bacteria in sediment (Smith & Samuelsen, 1996). Resistance development in fish pathogens is well documented including in *Aeromonas* spp, *Vibrio* spp, *Yersinia ruckerii* and *Edwardsiella tarda*. Resistance development has also been described in Penaeid pathogens such as *Vibrio harveyi*.

Few studies have looked at the side effects in the target organisms. Nephro-toxicity (Hentschel *et al.*, 2005) and immune-modulation (Rijkers *et al.*, 1981) have both been described and prolonged exposure to oxytetracycline is known to strongly up-regulate stress levels (Romero *et al.*, 2012) in zebra fish (*Danio rerio*).

Duran & Marshall (2005) identified a potential public health risk in ready to eat shrimp which tested positive for isolates of drug resistant bacteria and could act as vectors for the spread of antibiotic resistance.

Burridge *et al.* (2010) looked at usage of chemicals in salmon aquaculture in four countries (Norway, Chile, UK & Canada). A number of potential areas of concern were identified but not quantified: Effects on the biodiversity of plankton; selection of resistant bacteria; development of multi-drug resistant bacteria; food safety issues due to antibiotic contamination of the food chain. A general reduction in antibiotic usage was noted but with a large variation in usage between jurisdictions. Burridge *et al.* (2012) also looked at the use of pesticides for sea lice control, and considered the use of disinfectants and anaesthetics. In respect of the use of pesticides a potential concern was the impact on non-target organisms, especially crustaceans. The paper concluded that negative impacts on non-target organisms, if they occur, are minor. In recent years resistance in sea lice to both topical baths with pyrethroids or hydrogen peroxide and the in-feed treatments (emamectin) has brought the flubenzuron (di- and teflubenzuron) back into use in Norway. Field sampling around a research facility treating with teflubenzuron showed some residue in crustaceans (brown crab and spiny lobster). Laboratory studies carried out on juvenile lobsters show adverse effects (Samuelsen and Agnalt, 2014)

Anaesthetic use was considered of little risk due to low volumes and infrequent usage. Telfer *et al.* (2006) examined the environmental effects of emamectin benzoate used as an anti-sea lice treatment. The study found that residues in blue mussels 100 metres from the treated cages were fully depurated within one month. Residues in the sediment 10 metres from the cages also depurated post treatment but at a slower rate with residues detectable up to 12 months post treatment. Pruden *et al.* (2013) reviewed the management options to reduce the release of antibiotics into the environment. Four options were explored; the use of vaccines, increased bio-security, better feeding control to reduce waste feed, the use of dried food pellets in place of wet diets. Banerjee *et al.* (2014) also addressed the issue of remediation of drug use in aquaculture through management and treatment of effluent linked with macrophyte based remediation. The rapid detection and diagnosis of disease was identified as a prerequisite to reduce antibiotic use. The development of novel vaccines together with novel delivery mechanisms is also considered to have potential to significantly reduce therapeutic use. Chowdhury *et al.* (2012) studied the use of chemicals in freshwater aquaculture in Bangladesh and concluded that over use was exacerbated by an inappropriate level of knowledge at farm level and pointed to the need for edu-

cation programmes and in particular outreach programmes by the relevant authorities and agencies.

Romero *et al.* (2012) in their review explored the alternatives to the use of therapeutics including the use of probiotics, essential oils and phage therapy. Probiotics have been utilised with some success in teleost fish (Dimitroglou *et al.*, 2011; Merrifield *et al.*, 2010), in crustaceans (Van Hai *et al.*, 2009; Farzanfar *et al.*, 2006) and in bivalves (Kesarkodiwatson *et al.*, 2008; Prado *et al.*, 2010). The mechanism of action may be by way of immune-modulation, enhanced resistance or the production of inhibitory compounds. Essential oils, many of which contain phenolic compounds, have also been used to reduce bacterial infection in Penaeid culture (Randrianarivelo *et al.*, 2010; Sarter *et al.*, 2011) and in Tilapia (Immanuel *et al.*, 2009) and trout (Navarrete *et al.*, 2010). Phage therapy as a technique was initiated by Nakai *et al.* (1999). It has been used successfully in *Seriola* spp. (Nakai & Park, 2002; Almeida *et al.*, 2009). It has also been effective in shrimp and prawn culture against *Vibrio* spp. (Shivu *et al.*, 2007) and in trout culture against *Aeromonas salmonicida* (Imbeault *et al.*, 2006).

References

- Almeida, Adelaide *et al.* (2009): Phage therapy and photodynamic therapy: low environmental impact approaches to inactivate microorganisms in fish farming plants. In: Marine drugs. 7 (3), pp. 268-313.
- Banerjee, Soumik, Vikram Kumar; A.N. Pathak (2014). Drug Effects on aquaculture and its remediation. In: Journal of Drug Delivery & Therapeutics. 4(1) 117-122.
- Burridge, Les *et al.* (2010): Chemical use in salmon aquaculture: A review of current practices and possible environmental effects. In: Aquaculture. Elsevier B.V. 306 (1-4), pp. 7-23.
- Chowdhury, A.K. Jilani; Debasish Saha; M. Belal Hossain; M. Shamsuddin and Maruf Hossain Minar (2012). Chemicals Used in Freshwater Aquaculture with Special Emphasis to Fish Health Management of Noakhali, Bangladesh. In: African Journal of Basic & Applied Sciences 4 (4): 110-114.
- Defoirdt, Tom; Sorgeloos, Patrick; Bossier, Peter (2011): Alternatives to antibiotics for the control of bacterial disease in aquaculture. In: Current opinion in microbiology. 14 (3), pp. 251-8.
- Dimitroglou, Arkadios *et al.* (2011): Microbial manipulations to improve fish health and production-a Mediterranean perspective. In: Fish & shellfish immunology. Elsevier Ltd 30 (1), pp. 1-16.
- Duran, G.M; Marshall, Douglas (2005): Ready-to-eat shrimp as an international vehicle of antibiotic-resistant bacteria. In: Journal of Food Protection. 68 (11), pp. 2395-2401.
- Farzanfar, Ali (2006): The use of probiotics in shrimp aquaculture. In: FEMS immunology and medical microbiology. 48 (2), pp. 149-58.
- Hentschel, Dirk M *et al.* (2005): Acute renal failure in zebrafish: a novel system to study a complex disease. In: American journal of physiology. Renal physiology. 288 (5), pp. F923-9.
- Imbeault, Sandra *et al.* (2006): Using Bacteriophages to Prevent Furunculosis Caused by *Aeromonas salmonicida* in Farmed Brook Trout. In: Journal of Aquatic Animal Health. 18 (3), pp. 203-214.
- Immanuel, G *et al.* (2009): Dietary medicinal plant extracts improve growth, immune activity and survival of tilapia *Oreochromis mossambicus*. In: Journal of fish biology. 74 (7), pp. 1462-75.
- Kesarkodiwatson, A *et al.* (2008): Probiotics in aquaculture: The need, principles and mechanisms of action and screening processes. In: Aquaculture. 274 (1), pp. 1-14.

- Merrifield, Daniel L. *et al.* (2010): The current status and future focus of probiotic and prebiotic applications for salmonids. In: *Aquaculture*. Elsevier B.V. 302 (1-2), pp. 1-18.
- Nakai, T *et al.* (1999): Protective effects of bacteriophage on experimental *Lactococcus garvieae* infection in yellowtail. In: *Diseases of aquatic organisms*. 37 (1), pp. 33-41.
- Nakai, Toshihiro; Park, Se Chang (2002): Bacteriophage therapy of infectious diseases in aquaculture. In: *Research in microbiology*. 153 (1), pp. 13-8.
- Navarrete, Paola *et al.* (2010): Effect of *Thymus vulgaris* essential oil on intestinal bacterial microbiota of rainbow trout, *Oncorhynchus mykiss* (Walbaum) and bacterial isolates. In: *Aquaculture Research*. pp. 667-678.
- Park, Se Chang; Nakai, Toshihiro (2003): Bacteriophage control of *Pseudomonas plecoglossicida* infection in ayu *Plecoglossus altivelis*. In: *Diseases of Aquatic Organisms*. 53, pp. 33-39.
- Prado, Susana; Romalde, Jesús L; Barja, Juan L (2010): Review of probiotics for use in bivalve hatcheries. In: *Veterinary Microbiology*. 145 (3-4), pp. 187-97.
- Pruden, A. *Et al.* (2013): Management Options for Reducing the Release of Antibiotics and Antibiotic Resistance Genes to the Environment. In: *Environmental Health Perspectives*. 121(8), pp. 878-884.
- Randrianarivelo, R *et al.* (2010): Novel alternative to antibiotics in shrimp hatchery: effects of the essential oil of *Cinnamosma fragrans* on survival and bacterial concentration of *Penaeus monodon* larvae. In: *Journal of applied microbiology*. 109 (2), pp. 642-50.
- Rijkers, G.T. Oosterom, R. Van; Muiswinkel, W.B. Van (1981): The immune system of cyprinid fish. Oxytetracycline and the regulation of humoral immunity in carp (*Cyprinus carpio*). In: *Veterinary immunology and immunopathology*. 2 (3), pp. 281-290.
- Romero, Jaime; Carmen Gloria Feijoo and Paola Navarrete (2012): Antibiotics in Aquaculture – Use, Abuse and Alternatives, Health and Environment in Aquaculture, Dr. Edmir Carvalho (Ed.), ISBN: 978-953-51-0497-1, InTech, Available from: <http://www.intechopen.com/books/health-and-environment-in-aquaculture/antibioticsin-aquaculture-use-abuse-and-alternatives>.
- Samuelsen, O.B., Lunestad, B.T., Farestveit, E., Grefsrud, E.S., Hannisdal, R., Holmelid, B., Tjensvoll, T. & Agnalt, A.L. 2014. Mortality and deformities in European lobster (*Homarus gammarus*) juveniles exposed to the anti-parasitic drug teflubenzuron. *Aquat Toxicol.* 2014 Apr;149:8-15. doi: 10.1016/j.aquatox.2014.01.019
- Sarter, Samira *et al.* (2011): Antimicrobial Effects of Essential Oils of *Cinnamosma fragrans* on the Bacterial Communities in the Rearing Water of *Penaeus monodon* Larvae. In: *Vector-Borne and Zoonotic Diseases*. Mary Ann Liebert, Inc., publishers 11 (4), pp. 433-437.
- Shivu, Mockshanath M *et al.* (2007): Molecular characterization of *Vibrio harveyi* bacteriophages isolated from aquaculture environments along the coast of India. In: *Environmental microbiology*. 9 (2), pp. 322-31.
- Smith, Peter; Samuelsen, Ole B (1996): Estimates of the significance of out-washing of oxytetracycline from sediments under Atlantic salmon sea-cages. In: *Aquaculture*. 144 (1-3), pp. 17-26.
- Telfer, T.C. *et al.* (2006): Environmental effects of the anti-sea lice (Copepoda: Caligidae) therapeutic emamectin benzoate under commercial use conditions in the marine environment. In: *Aquaculture* 260, pp. 163–180.
- Van Hai, Ngo; Buller, Nicky; Fotadar, Ravi (2009): The use of customised probiotics in the cultivation of western king prawns (*Penaeus latissulcatus* Kishinouye, 1896). In: *Fish & shellfish immunology*. Elsevier Ltd 27 (2), pp. 100-4.

4.5 Transmission of sea lice and other parasites to wild populations (Nabeil Salama, Matt Gubbins and Stuart Middlemas, Scotland; Karin Kroon Boxaspen, Norway; Dave Jackson, Ireland; Knud Simonsen, Faroes)

Sea or salmon lice are ubiquitous, naturally occurring copepodid ectoparasites of the family Caligidae. Although there are some 600 described species, the native species which are predominantly of interest when considering the relationship between salmonid aquaculture and wild fish in the north-east Atlantic are: *Lepeophtheirus salmonis* (Kroyer 1837) and *Caligus elongatus* (Nordmann 1832); (Finstad & Bjørn 2011). *Lepeophtheirus salmonis* has a distribution across the northern hemisphere and has been reported to parasitise a range of wild fish predominantly *Salmo* and *Oncorhynchus* species but also occasionally non-salmonid fish (Boxshall 2013). However, this section will focus on *L. salmonis* primarily as a specialist parasite of salmonids in the north Atlantic.

The life-cycle of the sea louse has recently been re-described by Hamre *et al.* (2013) aligning the characteristics of *L. salmonis* with those of the wider Caligidae. From egg hatching, the lice undergo a development through two nauplii stages in the marine environment. An infective copepodid stage follows. Upon settlement, the life-cycle proceeds with two fixed chalimus stages, two mobile pre-adult stages and a reproducing adult stage producing eggs which once released are transported by the environment between hosts. This enables the situation whereby returning adult salmon, carrying gravid females are able to transmit lice to farmed salmon and vice versa. Due to the high number of individual farmed salmon compared to the number of wild salmonids at any given time in the marine environment there is the potential for lice populations to be magnified (Asplin *et al.*, 2011; Murray 2009), and shed lice back in to the aquatic environment.

C. elongatus is a generalist ectoparasite of some 80 species of marine fish and can transmit between host species (Kabata 1979). *C. elongatus* parasitism on farmed salmon in Scotland has been documented (Wootten *et al.* 1982; Bron *et al.* 1993b; Grant & Treasurer 1993). However it gains little attention with comparison with *L. salmonis*, although wild sea trout in Scotland was observed to have similar abundance and prevalence for *C. elongatus* as *L. salmonis* (Urquhart, *et al.* 2009). Heuch *et al.* (2007) surveyed a diverse number of wild fish species in Norway and found that 15% harboured *C. elongatus* but with variation in prevalence and abundance between the species. Todd (2007) reports that cod and haddock have been surveyed with settlement of 35 and 15 mobile stage lice which is claimed could have similar physiological effects to these hosts as salmonids with similar settlement of *L. salmonis*. Revie *et al.* (2002) described the epidemiology of *C. elongatus* from 58 Scottish salmon farms over a four year period and describe that there is a mean abundance of 4.0 lice per fish in the first year of production and 1.8 lice per fish in the second year of production, and follows a seasonal pattern. These differ to patterns in farms in Norway (Wallace 1998) and Ireland (Jackson *et al.* 2000), and is postulated in Scotland to be related to migration of wild teleost fish.

4.5.1 Drivers & Pressures

Within the ICES region Atlantic salmon is being farmed in Canada, Ireland, Scotland, Faroese Islands and Norway with the latter producing the largest volumes. Salmon farms are sited in coastal areas, often within fjords or voes near-shore, sharing the marine environment with wild salmonid populations. Open-cage salmon farms allow for the transmission of disease causing agents (Frazer 2009) to be transported from infectious wild fish, and if uncontrolled on the farmed fish, can magnify the agent load which is then shed back in to the environment where it could expose wild fish. Systems of inspection and reporting of sea lice levels is in place for all salmon farming countries in the ICES area, and in most cases delousing treatments are issued if a

defined threshold is exceeded. Below is a brief (and preliminary) overview of the monitoring practice and the threshold limits in the main salmon producing countries. Monitoring and management practices across the ICES region are summarised in Tables 3 and 4.

Table 3. Broad criteria for monitoring of sea lice treatments

	Norway	Scotland	Ireland	Faroe Isl.	Canada				USA
					British Columbia	New Brunswick	Newfoundland and Labrador	Nova Scotia	
Frequency	Temperature (3 m) dependent: T < 4°C: Biweekly 4°C < T: Weekly None, if slaughter to human consumption is expected within 2 weeks	Weekly	March-May: Biweekly Feb. and June-Nov: Monthly Jan-Dec: Once	Minimum: May – Dec: Biweekly Jan – April: Monthly Practice: All year: Biweekly	March-June: Biweekly July-Feb: Monthly but biweekly if meet threshold may be suspended for fush health or env. concerns	T > 5°C: Weekly 5°C < T: Monthly may be suspended for fish health or env. concerns	Dec-May: Monthly – Bimonthly 5°C < T: Weekly-biweekly T > 5°C: Weekly may be suspended for fush health or env. concerns	Weekly	
Sea Lices	<i>L. salmonis</i>	<i>L. salmonis</i> <i>C. elongatus</i>	<i>L. salmonis</i> <i>C. elongatus</i>	<i>L. salmonis</i> <i>C. elongatus</i>	<i>L. salmonis</i>				
Stages counted	Adult females motile attached	L.S.: adult females, mobiles C.E.: all stages grouped together	Adult females Total mobile lice	Adult females motile attached	<i>L. salmonis</i> Adult and preadult Adult female <i>C. elongatus</i> Motile	<i>L. salmonis</i> Adult male /preadults Adult female <i>C. elongatus</i> Motile <i>Chalimus</i> as <i>L. Salmonis</i> , but nut specified	<i>L. salmonis</i> Adult male /preadults Adult female <i>C. elongatus</i> Motile <i>Chalimus</i> as <i>L. Salmonis</i> , but nut specified	<i>L. salmonis</i> Adult male /preadults Adult female <i>C. elongatus</i> Motile <i>Chalimus</i> as <i>L. Salmonis</i> , but nut specified	
Cages/site	More than 3 cages: 50% Otherwise: 100%	A minimum of 5 cages	One standard, one random	Min: 2 standard and 2 random. Practice: Min – all cages	Minimum of 3 cages; one standard	6 cages	Minimum: 3 cages	6 cages	
Number of fish	June-Jan: 10/cage Feb-May:	In total: a minimum of 25	In total: 60, 30/cage for each yearclass	10/cage	Total: 60 fish 20/cage	Total: 30 fish 5/cage	Total: 15 fish 5/cage		

	20/cage	More than 5 cages: 5/cage					If >30lice on first 15 fish: More pens		
Counted by	Farmer	Farmer	Marine Institute	Aquacult. Res. Stn.	Farmer				
Reporting	Weekly to authorities	Counts reported weekly to other farmers within defined production area. Regular reporting to SSPO for Health management reports. At the request of Marine Scotland for inspection. Adverse treatments reported to veterinary medicines authority. Continued failed treatment reported to Marine Scotland.	Monthly to farmers, authorities and other interested organizations	<24h after counting to farmer and authorities	Monthly to authorities (DFO)	Submitted to regulator and communicated to farmer	Submitted to regulator and communicated to farmer	Managed by NSD. Communicated to farmers.	

Table 4. Broad criteria for actions resulting from the monitoring of sea lice treatments.

	Norway	Scotland	Ireland	Faroe Isl.	Canada				USA
Threshold (lice/fish)	0.5 adult female During zonal delousing spring campaign: 0.1 adult female	<i>L. salmonis</i> : Feb-June: 0.5 adult female July. - Jan 1.0 adult female <i>C. elongatus</i> : as appropriate for fish welfare. Threshold exceedence triggers reporting not mandatory treatment.	March-April 0.3-0.5 motile May-Feb: 2 adult female	2 adult females and 10 motile Some companies: 0.5 adult females	All year: 3 motile	TBA	none	none	Maine: 1.0 adult females, 5 adult
Time limits for treatment after recording and reporting	Within 2 weeks			Within 2 weeks					
Requirement for treatment	Closed units (since Jan., 2011)			Closed units (since May, 2012)					
References	http://lovdata.no/dokument/	www.thecodeofgoodpractice.co.uk/cogp/	www.marine.ie/NR/rdonlyres/0210E4CE-F4AA-47F2-8D51-EFEA10A4C4EB/0/	Www.logir.fo (Regulation no. 163 21.12.2009).	Saksida, S., et. al., Monitoring for sealice on farmed salmon in western and eastern Canada, Section D, in CSAS: Sea lice monitoring and non-chemical measures.				M. Roth, Integrated pest management

	<u>SF/forskrift/2012-12-05-1140</u>	3-fish-health-and-biosecurity/3-4-ongrowing/3-4-3-sea-lice	MonitoringProtocol3.pdf	K. Eliassen, pers. Com. Www.fiskaaling.fo		of sea lice in salmon aquaculture, presentation held nov. 29, 2007.
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4.5.2 State

There have been well reported declines in both the numbers of Atlantic salmon and the level of marine survival throughout its range (Jackson *et al.*, 2013 a & b). There are likely to be a number of factors driving the range-wide decline in salmon including local factors influencing fish in rivers and coastal areas, and global factors influencing populations across broad geographical scales during their time on the high seas.

Scotland: Sea lice on farmed salmon are recorded and reported by the industry producer organisation (SSPO). Data are aggregated by region and published quarterly online as monthly average numbers of ovigerous female lice and treatment frequencies. Data suggest that there are very regionally variable lice levels and may pose regionally variable infection risks to wild fish. The presence of sea lice on wild sea trout is also monitored by the Rivers and Fisheries Trusts of Scotland (RAFTS). Sea trout sampled by sweep netting at 22 sites across Scotland and the abundance and prevalence of lice reported for 2011 and 2012 (<http://www.rafts.org.uk/wp-content/uploads/2013/01/RAFTS-Regional-Monitoring-Report-2012.pdf>).

Due to the constrained geographic locations of fish farms to the north west of the country it is unlikely that sea lice from fish farms are driving the overall Scotland-wide changes in abundance. However there is concern that they are having an impact locally. There is evidence that declines in catches of wild salmon have been steeper on the Scottish west coast than elsewhere in Scotland and Norway (Vollestad *et al.* 2009) although the authors stressed that this did not prove a causative link. Ford & Myers (2008) compared indices of salmon abundance on the East and West coasts of Scotland together with farm production data. They found a reduction in the catches and counts of salmon associated with increased production of farmed salmon. In addition Butler & Watt (2003) showed that rivers with farms had significantly lower abundances of juvenile salmon than those without farms.

There is also concern over potential impacts of sea lice on sea trout stocks in Scotland, particularly as rod catches of sea trout on the west coast are currently at historically low levels. However, it is also clear that areas without salmon farms, such as the Moray Firth, catches are also at historically low levels and it seems likely that, as for salmon, there are a number of factors driving the trends in sea trout catches seen around Scotland, with these factors likely to vary between areas.

Scientific evidence from Norway and Ireland indicates a detrimental effect of sea lice on salmon (e.g. Jackson *et al.* 2011; Jackson *et al.* 2013; Skilbrei *et al.* 2013; Krkosek *et al.* 2012). However, direct evidence of impacts on Scottish salmon and sea trout stocks are lacking. Middlemas *et al.* (2013) did find a significant relationship between sea lice infestations on sea trout and the distance to the nearest salmon farm. Infestation levels were highest when sea trout were sampled close to a salmon farm and dropped off as the distance to the nearest farm increased. This suggests that there is a potential risk to sea trout in Scotland, although it does not enable the level of risk to the stocks to be determined.

Norway: All salmon farming sites in Norway report the numbers of salmon lice on the fish on a weekly basis when the temperature is above 4 °C. This is reported together with fish biomass and number of individual salmon per cage. Based on the number of sexually mature female salmon lice on the fish on each farming site, the number of infectious salmon lice larvae produced from the different salmon farms are calculated (Jansen *et al.*, 2012).

Salmon lice (*Lepeophtheirus salmonis*) from salmon farms pose an important threat to anadromous salmonids in Norwegian coastal waters (Serra-Llinares *et al.*, 2014). Salmon lice on farmed salmon produce large amounts of planktonic larvae stages that spread via the water currents and can infect migrating Atlantic salmon postsmolts, as well as sea trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*) that stay in coastal waters (Jones and Beamish, 2011). Hydrodynamic models coupled with biological data show that salmon lice can be transported up to 200 km over a 10-day period, although most dispersed 20-30 km (Asplin *et al.*, 2011; Serra-Llinares *et al.*, 2014).

Ireland: Jackson *et al.* (2013 a & b) found no geographic correlation between the presence of salmon farms and failure of rivers to meet their Conservation Limits at a River Basin District level. In fact, the rivers in the River Basin Districts with salmon farms performed best in terms of meeting their Conservation Limits and also in terms of ability to support a commercial catch by way of a commercial draft net fishery. The absence of any geographical correlation between the presence of salmon farms and poor performance of wild stocks is consistent with findings of previous research which found sea lice are a minor and irregular component in marine mortality. Jackson *et al.* (2011) reporting on a long term study carried out on Ireland's west coast showed that while treatment with SLICE® generally resulted in a higher percentage return than the untreated control group (9 out of 10 cases, sign test) in the majority of releases, six out of ten, this difference was not significant when compared using chi-squared tests. Over the period of the study the relationships between rates of return for treated and control batches exhibited similar trends and the level of infestation pressure by *L. salmonis* experienced by the outwardly migrating smolts was not of a level to be a consistently significant source of additional marine mortality. No significant difference in survival rates was found between treated and unprotected groups. The authors concluded that the highly significant decline in marine survival over the study period was independent of whether the fish were treated to protect against infestation with sea lice or not.

4.5.3 Impact

Reports of physiological hindrance of wild fish through sea lice parasitism pre-date salmonid aquaculture with first written records originating from the 1750s (Torrissen *et al.* 2013). Reports from Lewis, Scotland (Calderwood 1905) describe signs later asserted to be attributed to sea lice infestation by White (1940) in a description of a sea lice epizootic event of wild fish from Nova Scotia, Canada. The interest in sea lice parasitism emerged with the development of commercial Atlantic salmon aquaculture in the 1970's warranting the development of anti-parasitic treatments (Brandal *et al.* 1976; Brandal & Egilus 1977). Management of sea lice remains a high priority for salmon producers, providing a substantial production cost estimated to be over €300 million per year (Costello 2009) to the global industry.

Sea lice do not feed until post-settlement stages (Johnson & Albright 1991) and predominantly graze on mucus and epidermis (Wooten *et al.* 1982), although ingested host blood has been occasionally observed (Brandal *et al.* 1976). The feeding of lice can result in measurable physiological responses and are likely to be due to changes in osmotic regulation (Boxaspen 2006). Under artificial experimental exposure, it has been demonstrated that no physiological responses occur in smolt host until after the chalimus stage (Grimnes & Jackobsen 1996) whereby up to 250 settled chalimus lice result in no physical response. Physiological responses to mobile stage lice have been reported from experimental challenges with Wells *et al.* (2006) describing a physiological threshold for 19–70g newly seawater transferred sea trout smolt as being 12-13

mobile lice per fish, although it proposed that this would reduce survivability, mortality was not observed. More recent work provide similar numbers for mobile stage lice as causing a detriment to physiology; Skaala *et al.* (2014) highlight that 0.1 lice per gram seems to be a burden threshold, for small sea trout up to 1kg, whereas 40g smolt are reported as being compromised when settlement is above 0.75 chalimus stage lice per g (Finstad *et al.* 2000). Whilst 10 lice per fish for sea trout in their first year has also been suggested for Norway (Finstad & Bjørn 2011). Grimnes & Jacobsen (1996) observe mortality of small smolt with 30 settled mobile stage lice.

Individual physiological effects have been described for larger fish; for example experimental work has shown sub-lethal effects on adult salmon, whereby burdens within the range of 0.2-0.13 lice/g cause altered swimming performance (Wagner *et al.* 2003). However, observations of lice on wild returning salmon have indicated that salmon weighing 2.2–2.7kg have a mean number of mobile lice ranging between 17–31 mobile lice, but there is no discussion of salmon condition/physiology although host condition was not related to lice infestation levels in 1SW returns (Todd *et al.* 2007). Additionally, farmed fish have been recorded as being parasitised by up to 2000 lice (Brandal & Egidius 1977), indicating that larger fish may be less susceptible to lice settlement.

Although physiological observations under experimental conditions have been made for individuals, extrapolating such observations to determine the effect of sea lice parasitism on wild fish populations is more ambiguous. Recent work from Ireland (Jackson *et al.* 2011; 2013) and Norway (Skilbrei *et al.* 2013; Vollset *et al.* 2014) involving long term mark re-capture of anti-parasite treated (note that the treatment is not sea lice specific) and untreated control salmon smolts released, and meta-analysis of the data from both countries (Krkosek *et al.* 2012) demonstrate that there is very high marine mortality of both control and treated smolt, in all years and all systems, with substantial yearly variation in the returns of treated and untreated smolts leading to Jackson *et al.* 2011 stating: “the salmon louse being a minor component of marine mortality” with Krkošek *et al.* (2012) indicating that this results in some two-fifths reduction in adult recruitment in untreated salmon.

The direct transmission between farmed and wild fish is difficult to observe due to the nature of the aquatic environment, however inference has been made relating the presence of farms and the abundance of lice in the environment (Penston & Davies 2009), and that there is a correspondence between the lice counts on farms and the number of plankton stage lice sampled in the vicinity (Penston *et al.* 2008), similarly there is an association between farms and observations on wild sea trout (Middlemas *et al.* 2013), with observed counts reducing with increased distance from farms.

Although movement between hosts has been reported for mobile stage lice (Ritchie 1997), and there is an ability for positive chemotactic response at short distances from potential hosts (Devine *et al.* 2000), the predominant mode of transmission is passively between hosts through the water movements in the aquatic environment (see Salama & Rabe 2013). The distance a louse can transport from a host is dependent on the hydrodynamic conditions of the environment, not only the currents but also the physical characteristics. Temperature dictates the maturation rate between the nauplii to copepodid stage (Boxaspen and Næss, 2000) and also the time spent during the infective copepodid stage (Stien *et al.* 2005), with general acceptance that a louse will become infective 50 degree days after hatching and require to settle on a host within a further 100 degree days (Asplin *et al.* 2014). Whilst lice are transported by the environment, there is a substantial removal from the population, as is the case with spe-

cies with r-selected life-histories such as parasites and marine species with plankton stages. Lice suffer mortality and also reduced settlement due to changes in salinity (Bricknell *et al.* 2006), furthermore larvae are consumed by plankton feeders such as mussels (Molloy *et al.* 2011; Bartsch *et al.* 2013). Due to the passive movement of plankton lice, hydrodynamics can result in lice being transported to regions void of hosts, both spatially in the surface layer and at depths (Johnsen *et al.* 2014; *in press*), and also temporally (Johnsen *et al.* *in press*). Modelling studies have suggested that in large fjordic systems lice could be transported at distances of 100's of km however the majority of lice are retained within a few 10's of km (Asplin *et al.* 2014; Brooks 2005), which is consistent with field observations of lice sampled on trout within approximately 30 km region from farms both in Ireland (Gargan *et al.* 2003) and Scotland (Middlemas *et al.* 2013). Similarly, Bjørn *et al.* (2001) observed that salmon, sea trout and charr sampled in areas containing fish farms had greater abundance of settled lice.

To date, there is no direct study of sea lice impacting on wild salmon populations in Scotland.

4.5.4 Response

Sea lice are currently controlled by a range of pharmaceuticals, predominantly through the use of, in-feed or bath treatments performed in enclosures in the sea or onboard well boats, but also management practices such as coordinated fallowing, stocking and treatment and cohabitation of cleaner fish as biological control agents.

In Scotland it is a legal requirement for farms to enter in to farm management agreements with neighbouring farms (or statements should it be a sole operator) and take in to account operational, other health and production requirements. The structure of the farm management areas is outlined in a code of good practice for finfish aquaculture (CoGP management group) which also contains a recommendation for lice to be limited to 0.5 Feb-Jun and 1.0 female gravids July – Jan.

Recently, the industry Producers Organisation in Scotland started producing a quarterly regional health report, which demonstrate that since its inception regional mean lice counts exceeded the recommended threshold in 26% of reporting months, predominantly towards the end of the year where treatment ceases pre-harvesting. Fish farms undertake counts, and must make counts available for inspection to government fish health inspectors under the Aquaculture and Fisheries Scotland Act 2013, but no mandatory reporting is required. It is within the power of the chief veterinary officer for Scotland to authorise a cull on welfare grounds, as a means of last resort.

Norwegian regulations state that all fish farms should have a plan for effective monitoring and control of sea lice. The plan will have to be coordinated with other aquaculture facilities within a specified geographic area. The extent of the geographical area has to be determined from hydrographic conditions and the location of fish farms, so the area is suitable for achieving an effective inspection and control. The legal treatment threshold at all times should be less than 0.5 adult female lice average per fish. Treatments should be undertaken to ensure that the amount of sea lice do not exceed this limit, including, if necessary, slaughtered fish.

Coordinated treatment is scheduled for every spring and should be carried out so that the effect occurs within a period that gives the lowest infection pressure on migrating wild salmon smolts. The legal treatment threshold level is then 0.1 adult female lice average per fish.

In Norway these weekly sea lice counts are reported to the National Food Safety Authority (NFSA) and also reported on an aggregated level based on the numbers from NSFA on the webpage www.lusedata.no run by the Producers Organisation (FHL).

The spread of salmon lice from fish farms to wild fish has been a major issue in the last decade for the management of sustainable aquaculture (Costello, 2009).

In the Faroe Islands regulations on monitoring the sea lice were introduced in 2009. The minimum requirements are fortnightly counts from May to December, and monthly in the months January to April with a minimum of 4 units and 10 fish from each cage. The monitoring is undertaken by a team at the Aquaculture Research Station (ARS) as a third independent party on the behalf of the farmers biweekly throughout the year, and mainly in more cages than the minimum legislative requirement. The results are reported to the respective farmer and the Food- and Veterinary Authority (FVA) within 24 hours. The sea lice species that are registered are *L. Salmonis* and *C. Elongatus*, divided into the stages of adult female, preadult + adult male, and attached. The legal treatment threshold is 2 adult female or 10 motile *L. Salmonis*, but some of the companies are practising a more strict threshold. The sea lice counts are transparent for the entire industry and are evaluated at monthly meet-

ings at ASR by representatives from all companies and FVA. These meetings are also used to discuss and organize common treatment efforts. In 2013 the industry agreed on a national wide coordinated delousing campaign in a four week window in April-May 2013. Due to its apparent success the campaign is repeated in 2014, but a month earlier.

In Scotland the potential impacts of sea lice on wild fisheries are also assessed on an application by application as part of the development consent process for fish farms as part of the Environmental Impact Assessment process and views on this assessment sought from Statutory Consultees including scientific advisors, the Nature Conservation Body and the local Fishery trust operating through an Association. In instances where sea lice control is predicted to be poor, leading to high risk to sensitive populations, this may result in withholding of development consent, however the uncertainties associated with the scientific advice often make for difficult decisions by planning authorities.

In Norway the national sea lice surveillance programme (for NFSA) coordinated by the Institute of Marine Research including the Norwegian Institute for Nature Research, Rådgivende Biologer and Uni Research maps the levels of sea lice on wild migrating post smolts of salmon (in spring) and the sea trout (May to September) along the whole coast exposed to salmon farming including reference stations in the south east where there are no farming activity.

For instance the surveillance results for 2013 indicate lower infection pressure along parts of western Norway and parts of Central Norway during spring and early summer, and that the sea lice levels on both sea trout smolt and salmon smolt was low during smolt migration. This may be due to measures taken by management and industry but may also be due to low temperatures and much freshwater late winter and spring. In Northern part however infection pressure was higher than in the previous year (2012). During summer in intensive fish farming areas along large parts of the Norwegian coast still the levels of sea lice on sea trout was significantly higher than in areas without farming, and negative physiological and ecological consequences are likely.

To establish more precise management practices, both in areas like the “National Salmon Fjords” (in Norway) and other coastal areas, the development and validation of accurate distribution and abundance models for the dispersion of planktonic lice larvae is needed; this could also be the basis for an area management system based on ‘maximum sustainable lice loads’ or ‘lice quotas.’ (Serra Llinares *et al.* 2014).

Ireland has invested considerable time and resources in developing a control and management strategy for sea lice infestations on farmed salmonids. This research dates back to the early 1990s and was the basis for the introduction of the first comprehensive lice monitoring programme (Jackson and Minchen, 1993). Subsequent research (Jackson *et al.*, 2000; Jackson *et al.*, 2002) informed the development of a set of management protocols published by the Department of Marine in 2000. The full implementation of these protocols resulted in improved sea lice control on farmed salmon. There has been a policy of utilising research to ensure that the most up to date and effective treatment and management regimes are in place to control sea lice on Irish farms and this has included research into techniques to assess the most effective treatment regimes (Sevatdal *et al.*, 2005) and the sources of sea lice infestation in the marine environment (Jackson *et al.*, 1997; Copley *et al.*, 2005; Copley *et al.*, 2007). The monitoring and control system in place is comprehensive, transparent and independent. Following the introduction of the “*Strategy for improved pest control on*

Irish salmon farms” in 2008 by the Department of Agriculture Fisheries and Food there were significant improvements in sea lice management in Ireland (Jackson, 2011). The Irish management and control system has low treatment trigger levels, is based on independent inspection regimes, has a robust follow-up on problem areas and the results of the independent state run inspection programme are published in full each year (O’Donohoe *et al.*, 2013). The control strategy is aimed at implementing a more strategic approach to lice control at a bay level and targeting efforts on the spring period where there is a potential for impacts on wild smolts embarking on their outward migration. Trends in sea lice infestation on farmed fish (Figure 1) in May, the peak period for wild salmon smolt migration have shown a strong downward trend since the introduction of the new management strategy (Jackson *et al.*, 2013).

References

- Anon. Department of Agriculture Fisheries & Food 2008. A strategy for improved pest control on Irish salmon farms. May 2008. 51pp. Ireland.
- Asplin L., Boxaspen K. K. & Sandvik A. 2011 Modeling the distribution and abundance of planktonic larval stages of *Lepeophtheirus salmonis* in Norway. In: *Salmon Lice: An Integrated Approach to Understanding Parasite Abundance and Distribution* (Ed. by S Jones & R. Beamish), pp 31-50 Wiley-Blackwell, Oxford, UK.
- Asplin, L., Johnsen, I. A., Sandvik, A. D., Albretsen, J., Sundfjord, V., Aure, J., & Boxaspen, K. K. (2014). Dispersion of salmon lice in the Hardangerfjord. *Marine Biology Research*, 10: 216-225.
- Bartsch A, Robinson SMC, Liutkus M, Ang KP, Webb J, Pearce CM (2013) Filtration of sea louse, *Lepeophtheirus salmonis*, copepodids by the blue mussel, *Mytilus edulis*, and the Atlantic sea scallop, *Placopecten magellanicus*, under different flow, light and copepodid-density regimes. *J Fish Dis* 36: 361–370
- Bjørn, P. A., Finstad, B, Kristoffersen, R. (2001). Salmon lice infection of wild sea trout and Arctic char in marine and freshwaters: effects of salmon farms. *Aquaculture Research* 32, 947–962.
- Boxaspen K. & Naess T. 2000. Development of eggs and the planktonic stages of salmon lice (*Lepeophtheirus salmonis*) at low temperatures. *Contributions to Zoology* 2000;69:51-55.
- Boxaspen K (2006) A review of the biology and genetics of sea lice ICES journal of Marine Science 63:1304 – 1316.
- Boxshall G. (2013). *Lepeophtheirus salmonis* (Krøyer , 1837). In: Walter, T.C. & Boxshall, G. (2013). *World of Copepods database*. Accessed through: World Register of Marine Species at: <http://goo.gl/d3ZeRn> [Accessed 26 March 2014]
- Brandal P.O. & Egidius E. (1977) Preliminary report on oral treatment against salmon lice, *Lepeophtheirus salmonis*, with Neguvon. *Aquaculture* 10: 177–178.
- Brandal P.O. & Egidius E. (1979) Treatment of salmon lice (*Lepeophtheirus salmonis* Krøyer , 1838) with Neguvon® —description of method and equipment. *Aquaculture* 18:183–188.
- Bricknell, I. R., Dalesman, S. J., O Shea, B., Pert, C. C., & Mordue Luntz, A. J. (2006). Effect of environmental salinity on sea lice *Lepeophtheirus salmonis* settlement success. *Diseases of aquatic organisms* 71; 201- 2012.
- Brooks, K. 2005. The effects of water temperature, salinity, and currents on the survival and distribution of the infective copepodid stage of sea lice (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada. *Rev. Fish. Sci.*, 13: 177–204.
- Bron JE, Sommerville C, Wooten R, Rae GH (1993) Influence of treatments with dichlorvos on the epidemiology of *Lepeophtheirus salmonis* (Krøyer 1837) and *Caligus elongatus*

- (Nordmann 1832) on Scottish salmon farms. In *Pathogens of Wild and Farmed Fish: Sea Lice* (eds Boxshall GA, DeFaye D) pp 263 - 274, Ellis Horwood, Chishester
- Butler JRA & Watt J. 2003. Assessing and managing the impacts of marine salmon farms on wild Atlantic salmon in western Scotland: identifying priority rivers for conservation. Pp. 93-118 in: Mills D (ed.). *Salmon at the Edge*. Blackwell Science, Oxford
- Calderwood WL (1905) "The white spot" affecting salmon in the island of Lewis . Annual report of the fishery board for Scotland. 25(2): 78-79
- Copley, L., Tierney, T. D., Kane, F., Naughton, O., Kennedy, S., O'Donohoe, P., Jackson, D. & McGrath, D., 2005. Sea lice, *Lepeophtheirus salmonis* and *Caligus elongatus*, levels on salmon returning to the west coast of Ireland, 2003. *Journal of the Marine Biological Association of the U. K.*, 85, 87-92.
- Copley L, O'Donohoe P, Kennedy S, Tierney D, Naughton O, Kane F, Jackson D & McGrath D 2007. Lice infestation pressures on farmed Atlantic salmon smolts (*Salmo salar* L.) in the west of Ireland following a SLICE (0.2% emamectin benzoate) treatment. *Fish Veterinary Journal* 9, pp 10–21.
- CoGP (Code of Good Practice) Management Group (2010) A code of good practice for Scottish finfish aquaculture. <http://www.thecodeofgoodpractice.co.uk/> [Accessed 26 March 2014]
- Costello, M. J. (2009). The global economic cost of sea lice to the salmonid farming industry. *Journal of Fish Diseases*, 32: 115–118
- Devine, G.J., Denholm, I., Horsberg, T.E., 2000. Chemotherapeutant resistance in sea lice: what is it and what can be done about it? *Caligus* 6, 12–14.
- FAO (Food and Agriculture Organization of the United Nations) (2008) World review of fisheries and aquaculture. FAO, Rome
- FAO (2012) The state of world fisheries and aquaculture - 2012. FAO, Rome
- Finstad, B. & Bjørn, P.A. 2011. Present status and implications of salmon lice on wild salmonids in norwegian coastal zones. - p. 281-305 in Jones, S. & Beamish, R. (eds.) *Salmon Lice: An integrated pproach to understanding parasite abundance and distribution*. Wiley-Blackwell, Oxford, UK.
- Finstad, B., Bjørn, P. A., Grimnes, A., & Hvidsten, N. A. (2000). Laboratory and field investigations of salmon lice [*Lepeophtheirus salmonis* (Krøyer)] infestation on Atlantic salmon (*Salmo salar* L.) post-smolts. *Aquaculture Research*, 31: 795-803.
- Ford, J. S., & Myers, R. A. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. *PLoS biology*, 6(2), e33..
- Frazer LN (2009) Sea cage aquaculture, sea lice, and declines of wild fish. *Conservation Biology* 23: 599–607
- Gargan, P. G., Tully, O., & Poole, W. R. (2003). The relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992–2001. *Salmon at the Edge*, 119-135.
- Grant AN, Treasurer J (1993) The effects of fallowing on caligid infestations on farmed Atlantic salmon (*Salmo salar* L.) in Scotland. In: (eds Boxshall GA, Defaye D) *Pathogens of wild and farmed fish: sea lice*. pp 256–260 Ellis Horwood, Chichester,
- Grimnes A, Jakobsen PJ (1996) The physiological effects of salmon lice infection on post-smolt of Atlantic salmon. *J Fish Biology* 48:1179–1194
- Hamre LA, Eichner C, Caipang CMA, Dalvin ST, Bron JE, *et al.* (2013) The Salmon Louse *Lepeophtheirus salmonis* (Copepoda: Caligidae) Life Cycle Has Only Two Chalimus Stages. *PLoS ONE* 8(9): e73539. doi:10.1371/journal.pone.0073539
- Heuch PA, Øines Ø, Knutsen JA, Schram TA (2007) Infection of wild fishes by the parasitic copepod *Caligus elongatus* on the south east coast of Norway. *Dis Aquat Org* 77:149-158

- Jackson, D. and Minchin, D. 1993. Lice infestations of farmed salmon in Ireland. In: Boxshall, G.A. and Defaye, D. (Eds.), *Pathogens of wild and farmed fish: sea lice*, Ellis Horwood Ltd., London.
- Jackson, D., Deady, S., Leahy, Y., & Hassett, D. 1997. Variations in parasitic caligid infestations on farmed salmonids and implications for their management. *ICES Journal of Marine Science*. 54: 1104-1112.
- Jackson D., Deady S., Hassett D. & Leahy Y. (2000) *Caligus elongatus* as parasites of farmed salmonids in Ireland. *Contributions to Zoology* 69: 65–70.
- Jackson, D., D. Hassett, S. Deady, Y. Leahy, 2000. *Lepeophtheirus salmonis* (Copepoda: Caligidae) on farmed salmon in Ireland. *Contributions to Zoology*. 69, 71-77.
- Jackson D., Hassett D. & Copley, L. 2002. Integrated lice management on Irish Salmon farms. *Fish Veterinary Journal*, (6) 28-38.
- Jackson, D, Cotter, D. OMaoileidigh, N., O'Donohoe, P., White, J., Kane, F., Kelly, S., McDermott, T., McEvoy, S., Drumm, A. and Cullen, A. (2011) Impact of early infestation with the salmon louse *Lepeophtheirus salmonis* on the subsequent survival of outwardly migrating Atlantic salmon, *Salmo salar* L., smolts. *Aquaculture*, 319: 37-40.
- Jackson 2011. Ireland: the development of sea lice management methods. In: *Salmon Lice: An Integrated Approach to Understanding Parasite Abundance and Distribution* (Ed. by S Jones & R. Beamish), pp 177-203 Wiley-Blackwell, Oxford, UK.
- Jackson D, O'Donohoe P, McDermott T, Kane F, Kelly S & Drumm A 2013. Report on Sea Lice Epidemiology and Management in Ireland with Particular Reference to Potential Interactions with Wild Salmon (*Salmo salar*) and Freshwater Pearl Mussel (*Margaritifera margaritifera*) Populations. *Irish Fisheries Bulletin* No 43, Marine Institute. <http://hdl.handle.net/10793/893>
- Jackson D, Mc Dermott T, Kane F, O'Donohoe P & Kelly S 2013. Evaluation of the impacts of aquaculture and freshwater habitat on the status of Atlantic salmon stocks in Ireland. *Agricultural Sciences*, 2013, Vol. 4, No. 6A, pp 62-67. <http://dx.doi.org/10.4236/as.2013.46A010>
- Jackson D., Cotter D., Newell J., McEvoy S., O'Donohoe P., Kane F., McDermott T., Kelly S. & Drumm A. 2013. Impact of *Lepeophtheirus salmonis* infestations on migrating Atlantic salmon, *Salmo salar* L., smolts at eight locations in Ireland with an analysis of lice-induced marine mortality. *Journal of Fish Diseases* 36 (3), 273-281. <http://dx.doi.org/10.1111/jfd.12054>
- Jackson, D., Kane, F., O'Donohoe, P., Mc Dermott, T., Kelly, S., Drumm, A. and Newell, J. (2013), Sea lice levels on wild Atlantic salmon, *Salmo salar* L., returning to the coast of Ireland. *Journal of Fish Diseases*, 36: 293–298
- Jansen PA, Kristoffersen AB, Viljugrein H, Jimenez D, Aldrin M, Stien A (2012) Sea lice as a density dependent constraint to salmonid farming. *Proc R Soc Lond B Biol Sci* 279: 2330–2338
- Johnsen, I.A., Fiksen, Ø., Sandvik, A.D., Asplin, L. (in press) Vertical salmon lice behavior as a response to environmental conditions and its influence on the regional dispersion in a fjord system. *Aquaculture Environment Interactions*
- Jones S. R. M. & Beamish R.J. 2011. *Lepeophtheirus salmonis* on salmonids in the northeast Pacific ocean. In: *Salmon Lice: An Integrated Approach to Understanding Parasite Abundance and Distribution* (Ed. by S Jones & R. Beamish), pp 307-329 Wiley-Blackwell, Oxford, UK.
- Kabata Z (1973) The species of *Lepeophtheirus* (Copepoda: Calidigidae) from the fishes of British Columbia. *Journal of the Fisheries Research Board of Canada* 30 : 729 – 759

- Krkošek, M., C. Revie, P. Gargan, O. Skilbrei, B. Finstad, & C. Todd. (2012). Impact of parasites on salmon recruitment in the Northeast Atlantic Ocean. *Proceedings of the Royal Society B*. 280: 20122359
- Middlemas S.J., Raffell J.A., Hay D.W., Hatton-Ellis M. & Armstrong J.D. (2010) Temporal and spatial patterns of sea lice levels on sea trout in western Scotland in relation to fish farm production cycles. *Biology Letters* 6, 548–551.
- Middlemas, S.J., Fryer, R.J., Tulett, D. & Armstrong, J.D. (2013) Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. *Fisheries Management & Ecology* 20: 68-74.
- Molloy SD, Pietrak MR, Bouchard DA, Bricknell I (2011) Ingestion of *Lepeophtheirus salmonis* by the blue mussel *Mytilus edulis*. *Aquaculture* 311: 61–64
- Munro LA, Wallace IS (2013) Scottish finfish production survey 2012 report. Scottish Government, Edinburgh. Available at: <http://www.scotland.gov.uk/Resource/0043/00433470.pdf> [Accessed 26 March 2014]
- Murray AG (2009) Using simple models to review the application and implications of different approaches used to simulate transmission of pathogens among aquatic animals. *Preventative Veterinary Medicine* 88:167 – 177
- O'Donohoe P, Kane F, Kelly S, McDermott T, Drumm A & Jackson D 2013. National Survey of Sea lice (*Lepeophtheirus salmonis* Krøyer and *Caligus elongatus* Nordmann) on Fish Farms in Ireland - 2012. *Irish Fisheries Bulletin* No 41, Marine Institute. <http://oar.marine.ie/handle/10793/861>
- Penston, M. J., Millar, C. P., Zuur, A. and Davies, I. M. (2008), Spatial and temporal distribution of *Lepeophtheirus salmonis* (Krøyer) larvae in a sea loch containing Atlantic salmon, *Salmo salar* L., farms on the north-west coast of Scotland. *Journal of Fish Diseases*, 31: 361–371
- Penston, M. J. and Davies, I. M. (2009), An assessment of salmon farms and wild salmonids as sources of *Lepeophtheirus salmonis* (Krøyer) copepodids in the water column in Loch Torridon, Scotland. *Journal of Fish Diseases*, 32: 75–88
- Penston MJ, McBeath AJA, Millar CP (2011) Densities of plankton *Lepeophtheirus salmonis* before and after an Atlantic salmon farm relocation . *Aquaculture Environment Interactions* 1: 225 – 232
- Revie CW, Gettinby G, Treasurer JW, Rae GH (2002) The epidemiology of the sea lice, *Caligus elongatus* Nordmann, in marine aquaculture of Atlantic salmon, *Salmo salar* L. in Scotland. *Journal of fish diseases* 25: 391 -399 .
- Ritchie G (1997) The host transfer ability of *Lepeophtheirus salmonis* (Copepoda: Caligidae) from farmed Atlantic salmon, *Salmo salar* L. *Journal of Fish Diseases* 20: 153–157
- Salama NKG, Rabe B (2013) Developing models for investigating the environmental transmission of disease-causing agents within open-cage salmon aquaculture. *Aquaculture Environment Interactions* 4:91 – 115.
- Samuelsen, O.B., Lunestad, B.T., Farestveit, E., Grefsrud, E.S., Hannisdal, R., Holmelid, B., Tjensvoll, T. & Agnalt, A.L. 2014. Mortality and deformities in European lobster (*Homarus gammarus*) juveniles exposed to the anti-parasitic drug teflubenzuron. *Aquat Toxicol.* 2014 Apr;149:8-15. doi: 10.1016/j.aquatox.2014.01.019
- Serra-Llinares, R.M., Bjørn, P.A., Finstad, B., Nilsen, R., Harbitz, A., Berg, M., Asplin, L. 2014. Salmon lice infection on wild salmonids in marine protected areas: an evaluation of the Norwegian National Salmon Fjords. *Aquaculture Environment Interactions* 5: 1–16.
- Sevatdal, S., Copley, L., Wallace, C., Jackson, D. and T. Horsberg 2005. Monitoring of the sensitivity of sea lice (*Lepeophtheirus salmonis*) to pyrethroids in Norway, Ireland and Scotland using bioassays and probit modelling. *Aquaculture* 244:19-27.

- Skaala, Ø., Johnsen, G. H., Lo, H., Borgstrøm, R., Wennevik, V., Hansen, M. M., ... & Barlaup, B. T. (2014). A conservation plan for Atlantic salmon (*Salmo salar*) and anadromous brown trout (*Salmo trutta*) in a region with intensive industrial use of aquatic habitats, the Hardangerfjord, western Norway. *Marine Biology Research*, 10: 308-322.
- Skilbrei O, Finstad B, Urdal K, Bakke G, Kroglund F, *et al.* (2013) Impact of early salmon louse, *Lepeophtheirus salmonis*, infestation and differences in survival and marine growth of sea-ranched atlantic salmon, *Salmo salar* L., smolts 1997–2009. *Journal Fish Diseases* 36: 249–260.
- Stien A, Bjørn PA, Heusch PA, Elston DA (2005) Population dynamics of salmon lice *Lepeophtheirus salmonis* on Atlantic salmon and sea trout *Marine Ecological Progress Series* 290: 263 – 275 .
- Todd, C. D. (2007). The copepod parasite (*Lepeophtheirus salmonis* (Krøyer), *Caligus elongatus* Nordmann) interactions between wild and farmed Atlantic salmon (*Salmo salar* L.) and wild sea trout (*Salmo trutta* L.): a mini review. *Journal of Plankton Research*, 29, 61-71.
- Torrissen O, Jones S, Asche F, Guttermsen A, Skilbrei OT, Nilsen F, Horseberg TE, Jackson D (2013) salmon lice – impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases*. 36:171-194
- Urquhart, K., Pert, C. C., Fryer, R. J., Cook, P., Weir, S., Kilburn, R., & Bricknell, I. R. (2010). A survey of pathogens and metazoan parasites on wild sea trout (*Salmo trutta*) in Scottish waters. *ICES Journal of Marine Science: Journal du Conseil*, 67: 444-453.
- Vøllestad, L. A. *et al.* 2009 Divergent trends in anadromous salmonid populations in Norwegian and Scottish rivers. *Proc. Roy. Soc. B* 276, 1021-1027.
- Vollset, K. W., Barlaup, B. T., Skoglund, H., Normann, E. S., & Skilbrei, O. T. (2014). Salmon lice increase the age of returning Atlantic salmon. *Biology letters*, 10(1), 20130896.
- Wagner, G. N., McKinley, R. S., Bjørn, P. A. and Finstad, B. (2003), Physiological impact of sea lice on swimming performance of Atlantic salmon. *Journal of Fish Biology*, 62: 1000–1009.
- Wallace C. (1998) Possible causes of salmon lice *Lepeophtheirus salmonis* (Krøyer, 1837) infections on farmed atlantic salmon, *Salmo salar* L., in a western Norwegian fjord-situated fish farm.

4.6 Utilization of wild-fish trophic resources by mariculture

4.6.1 Fed culture (David Bengtson, USA)

The production of fish feed for common aquaculture species, like Atlantic salmon, has changed drastically over the last few decades. Whereas earlier diets for such species relied heavily on fish meal and fish oil derived from pelagic “industrial” species to meet the protein and lipid requirements of the cultured species, current diets rely increasingly on proteins and oils from non-fish products, especially plants. Fish meal and fish oil prices are quite variable and significantly more expensive compared to plant product prices. Both variable availability and high prices of fish meal and oil have driven considerable research in the past decade on substitute products to incorporate into aquaculture diets.

Fortunately, a recent review article (Shepherd and Jackson, 2013) summarizes trends in the use of fish meal and fish oil globally. The following points are drawn from their article:

- In 2009, 20.8 million metric tons (MMT) from capture fisheries were reduced to fish meal and fish oil (FAO, 2010), yielding about 4.8 MMT of fish meal and 1.05 MMT of fish oil.

- Beginning at about 3 MMT in the early 1960's, fish meal production peaked in 1994 at about 7.4 MMT, but only averaged 5.4 MMT in the period 2001-2011 and has generally been decreasing since 2004. The decline is thought to be due to increased fishing regulations (Mittaine, 2012).
- Fish oil production has varied from 0.9 to 1.2 MMT from 2001-2011, with a mean of 1.0 MMT.
- Use of fish meal in aquaculture feed has increased from 2% of total fish meal in 1960 to 10% in 1980 to 73% in 2010. Use of fish meal in animal feeds has greatly declined over that period as aquaculture feeds have taken a larger share. Primary aquaculture groups using fish meal, and the percentage of fish meal from aquaculture's total consumed by each are: crustaceans (29%), salmonids (24%), and marine finfish (23%).
- Aquaculture use of fish oil is decreasing in terms of MMT, but still makes up about 80% of global fish oil usage. Human direct consumption of fish oil is increasing and now makes up 15% of global fish oil usage.
- More than 50% of fish meal (possibly 60-70%) comes from the Peruvian anchovy fishery, the management of which has greatly improved (Aranda, 2009). This fishery, which is greatly reduced during El Niño conditions, is a major determinant of fish meal prices, particularly their variability during El Niño years.
- Major fish meal species in the OSPAR region are sandeels (*Ammodytes tobianus*), blue whiting (*Micromesistius poutassou*), sprat (*Sprattus sprattus*), and capelin (*Mallotus villosus*), with landings of 486,500 MMT, 678,500 MMT, 262,000 MMT, and 958,500 MMT, respectively (Wijkström, 2012). Although almost 90% of herring in Norway went for fish meal and oil 20-25 years ago, about 85% now goes for human consumption and only bad quality fish goes for reduction (Wijkström, 2012).
- Fish meal inclusion in diets for Atlantic salmon in Norway has declined from about 55% of diet composition in 1995 to about 28% in 2010. Similarly, fish oil inclusion has declined from about 27% in 1995 to about 16% in 2010. Those reductions were possible due to increased usage of alternative proteins and starch (from 17% in 1995 to 50% in 2010) and vegetable oil (0% in 1995 to 5% in 2010).
- Calculation of the Fish in to Fish Out (FIFO) ratio has become an important tool to determine whether aquaculture is a net user or net producer of seafood. Tacon and Metian (2008) calculated that aquaculture worldwide used 16.5 MMT of pelagic fishes (Fish In) in 2006 and produced 37.4 MMT of aquaculture product for a FIFO of 0.44. They calculated that the FIFO for salmonids diminished from 7.5 in 1995 to 4.9 in 2006. However, Jackson and Shepherd (2012) questioned their approach of treating fish meal and fish oil separately, because they come from the same fish; their revised calculations show that the salmonid aquaculture FIFO declined from 2.6 to 1.4 from 2000 to 2010, while salmonid production increased 53%.

A summary of recent articles on replacement of fish meal and fish oil in diets for salmonids:

- Pratoomyot *et al.* (2010) fed Atlantic salmon experimental diets with 35% protein, 28% lipid. The control diet contained 25% fish meal and 45% plant protein, the maximum plant protein inclusion level for salmon at that time, whereas other diets contained lesser percentages of fish meal, 18%, 11%

and 5%, with appropriate increases in plant material and added crystalline amino acids. Lipid requirement was met by a 40/60 mixture of rapeseed oil and fish oil. Fish grew significantly less on the 18%, 11% and 5% fish meal diets, indicating that the 25% fish meal level may be a required amount for successful Atlantic salmon production.

- Bendicksen *et al.* (2011) tested diets for Atlantic salmon containing 10, 15, or 20% fish meal and a 50/50 mixture of rapeseed oil and fish oil (although half of the fish oil was oil reclaimed from fish processing waste). They saw no significant difference in growth of these fish, suggesting that the level of fish meal might be reduced to as low as 10% in salmon diets. Their FIFO calculations indicate that fish oil may be more limiting on the growth of the salmon industry than fish meal.
- Boissy *et al.* (2011), while not conducting an actual experiment, used Life Cycle Assessment to estimate the environmental impacts of feeding Atlantic salmon and rainbow trout a Standard Diet (STD), with high levels of fish meal and fish oil, vs. a Low Marine-Fishery-Capture Diet (LFD), with reduced fish meal and no fish oil. The LFD scenario resulted in lower biotic resource use, as expected. The remainder of the environmental impacts depended on the geographical origin of the fishery products and the agriculture crop used as a substitute for fish oil.
- Overturf *et al.* (2013a, b) described a selective-breeding program for rainbow trout to produce families that rely less on fishery products. Their results indicate that rainbow trout can be selectively bred for this purpose.
- Liland *et al.* (2013) fed Atlantic salmon diets containing 70% replacement of fish meal with plant proteins and 80% replacement of fish oil either with olive oil, rapeseed oil, or soybean oil (control diet contained fish oil only). No significant differences in fish growth were observed among treatments. They concluded that net production of marine protein, but not marine omega-3 fatty acids, was obtained in fish fed these diets. Production of 1 kg of salmon required only 800 g of wild fish products, yielding a FIFO < 1.

The Sustainable Fisheries Partnership (SFP) web site provides information on the European Fishmeal & Oil Users Roundtable, which “focuses on monitoring sustainability status and issues of stocks used for fishmeal and fish oil production, discussing conditions to continue or resume sourcing, and pushing for improvements where they are needed.” In the European region, they focus on 23 individual fisheries, of which three are MSC-certified and 10 have public Fishery Improvement Plans. Thus, better management of these fisheries seems to be a priority. In addition, ICES provides advice on many of these fisheries.

Summary: Utilization of wild-fish trophic resources by fed culture

- The amounts of both fish meal and fish oil production have decreased in recent years.
- Aquaculture worldwide now uses the majority of both fish meal and fish oil produced.
- Research on the substitution of fish meal and fish oil with alternative products, mostly plant-based, has resulted in greatly decreased percentages of fish meal and fish oil in diets for the salmonid industry.
- The most recent research, at laboratory scale, indicates that Atlantic salmon can be grown with Fish in to Fish Out ratio < 1 .

Selective breeding of fish to produce families that can better utilize plant products, and therefore further reduce marine inputs to salmonid diets, is a promising area of research.

4.6.2 Non-fed bivalve culture (Peter Cranford, Canada)

Bivalves have an exceptional capacity to filter large volumes of water (reviewed by Cranford *et al.* 2011) to capture phytoplankton, pelagic protists, zooplankton and other suspended particulate matter ranging in size from 3 to approximately 3000 μm (Møhlenberg and Riisgård, 1978; Ward and Shumway, 2004; Lehane and Davenport, 2006; Zeldis *et al.*, 2004; Trottet *et al.*, 2008). Cultured bivalves compete with other benthic and pelagic filter feeders in the marine environment and may displace some species by out-competing them for similar trophic resources (Gibbs 2007). Depending on local conditions, the grazing activities of cultured bivalve populations may have no detectable environmental impact, may result in positive ecosystem services, or may have a controlling, and potentially destabilizing, influence on coastal ecosystem structure and function. Positive effects are generally believed to occur in areas where bivalve aquaculture serves as a manageable biofilter that improves water quality and lessens coastal eutrophication (e.g. Lindahl, 2011). Environmental interactions with bivalve aquaculture have been the topic of considerable study, and this effort has included the influence on many ecosystem processes responsible for energy flow and nutrient cycling, and planktonic and benthic communities. The focus of the following review is on the identification of coastal-scale changes in the availability of wild fish food resources that may occur from direct competition with cultured bivalves, or which may result from aquaculture-induced changes in the state of the ecosystem or ecosystem components.

Studies in bivalve ecology have emphasized that phytoplankton dynamics in coastal regions may be strongly coupled with bivalve filter-feeding activity to the extent that the bivalve community plays a major ecological role in controlling phytoplankton biomass and trophic structure (reviewed by Dame 1996). Both natural and cultured bivalve populations can exert simultaneous bottom-up (nutrient supply and light) and top-down (grazing) control of phytoplankton standing stock and production. However, the spatial extent and magnitude of this control is always site-specific with vulnerability depending on factors controlling food consumption (e.g. intensity of culture and food quantity/quality) and food resupply processes such as tidal flushing and primary production (e.g. Grant and Filgueira, 2011). Bivalve filter-feeding always results in some local reduction (depletion) of their food supply. If the bivalve culture is consuming trophic resources faster than they can be replaced by tidal flushing and phytoplankton growth, then the culture will become food limited and shellfish production will be less than maximal for that site (i.e. production carrying capacity sur-

passed). Studies on food depletion by bivalve aquaculture have generally focused on the suspended culture of species in the Mytilidae family. Measurements of food depletion inside mussel farms report between 10 and 80% removal of phytoplankton (Blanco *et al.*, 1996; Boyd and Heasman, 1998; Heasman *et al.*, 1998; Ogilvie *et al.*, 2000; Strohmeier *et al.*, 2005; Gibbs, 2007; Petersen *et al.*, 2008; Cranford *et al.* 2014) and 26 to 77% of different zooplankton groups (Maar *et al.*, 2008), and this can have a feedback effect on the growth and condition of the cultured stock (Bacher *et al.* 2003, Strohmeier *et al.*, 2005, Ferreira *et al.* 2007, Duarte *et al.* 2008).

If the spatial scale of phytoplankton depletion expands outward from extensive bivalve farming activities to include a significant fraction of a coastal area, then this alteration to the base of the food web may be expected to generate significant ecological costs to higher trophic levels. This pressure on natural food supplies can compromise the sustainability of mariculture in the area; decreasing growth and survival rates of bivalves when cultured at high density. Modelling has been the primary means of assessing potential ecosystem alterations from bivalve culture (reviewed by Grant and Filgueira, 2011). Phytoplankton depletion and/or food-limitation of mariculture production have been predicted to occur at the coastal-embayment scale in many coastal aquaculture areas (e.g. Heral 1993; Raillard and Ménesguen 1994; Smaal *et al.* 2001; Chapelle *et al.* 2000; Bacher *et al.* 1998 and 2003; Ferreira *et al.* 1998; Gibbs 2007). A commonly applied first-order approximation of the potential for bivalve grazers to control the phytoplankton is to compare the turnover times of water body components responsible for phytoplankton depletion (bivalve population clearance time) and supply (hydrodynamic residence time and phytoplankton growth constant). This simple “depletion index” approach provided early evidence of the capacity of bivalve populations to alter phytoplankton abundance at the coastal ecosystem scale (Cloern 1982; Officer *et al.* 1982; Nichols 1985; Smaal and Prins; 1993; Dame 1996; Dame and Prins 1998; Cranford *et al.* 1998). Measurements of high levels of bay-scale phytoplankton depletion in a mussel culture embayment by Cranford *et al.* (2008) and Grant *et al.* (2007) have confirmed similar conclusions from ecosystem model predictions (Dowd 2003; Dowd 2005; Cranford *et al.*, 2007; Grant *et al.* 2008; Filgueira and Grant 2009).

Large-scale phytoplankton depletion by bivalves may be expected to be accompanied by a shift in phytoplankton composition towards small algal cells as a result of the lower prey size limit imposed by the structure of the bivalve ctenidium. Bivalve suspension feeders effectively retain particles larger than 3 to 7 μm and retention efficiency rapidly declines for smaller particles (reviewed by Ward and Shumway 2004). Small nanoplankton and all picoplankton (photoautotrophic and heterotrophic) are therefore not effectively captured. In addition to occupying a size refugia that allows picophytoplankton to escape capture by bivalves, they may be expected to thrive under high bivalve grazing pressure because the pelagic protists that control their populations are also a trophic resource for bivalves (Dupuy *et al.* 1999; Maar *et al.* 2007; Nielsen and Maar 2007; Trottet *et al.* 2008). The rapid nutrient uptake and growth rates of small cells (Stockner, 1988) can also be enhanced by bivalve-mediated effects on light penetration and nutrient regeneration. Enclosure experiments in which *M. edulis* were sufficiently abundant to deplete nano- and microphytoplankton, showed that the picoplankton became dominant (Riemann *et al.* 1988; Olsson *et al.* 1992; Graneli *et al.* 1993). Size-selective bivalve grazing is cited for the high abundance of picophytoplankton in the Thau Lagoon, France (Courties *et al.* 1994; Vaquer *et al.* 1996; Dupuy *et al.*, 2000; Souchu *et al.*, 2001), in land-locked Norwegian oyster ponds (Klavenes, 1990), and in several other estuaries in Canada, Italy and The Netherlands

(Cranford *et al.* 2008; Caroppo 2000; Smaal *et al.* 2013). A shift towards small algae over a scale of 20 km was observed to accompany the significant depletion of phytoplankton in water passing a large natural mussel bed in the turbulent Öresund strait (Norén *et al.* 1999). These results largely confirm the hypothesis that intense bivalve grazing gives small phytoplankton a competitive advantage such that they dominate under conditions where bivalves exert significant control over the phytoplankton.

The numerous studies in the Oosterschelde estuary (the Netherlands), as described in Smaal *et al.* (2013), collectively produce a case study on the large-scale ecological effects of bivalve aquaculture. Nutrient concentrations in this estuary are generally low but primary production is nutrient limited only for short periods because of the regulating role of bivalves. Bivalve grazing and their effects on nutrient regeneration initially stimulated primary production and phytoplankton turnover. However, the total filtration capacity of bivalves stocks in the estuary increased by 30% between 1995 and 2009, and a point was reached where grazing pressure became the limiting factor for primary production. The resulting switch from bottom-up to top-down control of the phytoplankton was cited as the most likely cause for the observed 49% decline in primary production in the basin and the 38% decrease in the annual growth of wild commercial cockles.

A substantial weight of evidence exists to conclude that extensive bivalve aquaculture activities in several coastal areas in the ICES region have altered ecosystem structure and function as a result of their influence on low-trophic level resources; including the phytoplankton, pelagic ciliates and flagellates, zooplankton, and detritus. A general conclusion from ecosystem modelling is that bivalve aquaculture routes energy flow towards benthic food webs instead of the pelagic (e.g. Dame 1996, Cranford *et al.* 2007, Filgueira and Grant 2009). Ecosystem-scale control of the phytoplankton and other pelagic trophic resources by bivalve aquaculture would represent a significant trophic interaction that may upset critical ecological equilibria, possibly resulting in cascading food web changes that shift ecosystem structure, alter function and ultimately impact fish stocks. Beyond the direct effects of resource competition with other benthic and pelagic filter-feeders, it is difficult to measure how bivalve culture manifests itself in the food web to ultimately impact wild fish. Gibbs (2007) noted that several possible consequences can result from the combination of bivalve aquaculture; 1) reducing/replacing the role of zooplankton, 2) shifting benthic communities from filter- to deposit-feeders, and 3) redirecting energy flow and nutrient cycling in the microbial loop. In natural systems, the fate of phytoplankton is divided amongst benthic filter feeders, zooplankton and some end up as detritus (Figure 5). In systems with bivalve culture, some of the energy that previously flowed through the other three groups must now pass through the bivalve culture and less energy may be available to one or all of the other three groups (Figure 5). Effects on zooplankton may be expected based on their consumption by bivalves (Davenport *et al.* 2000), as well as direct competition for resources, and this will impact the food supply of small fish. Bivalve culture competes with the ecological role of zooplankton and may, under certain conditions, replace that role (Jiang and Gibbs, 2005, Gibbs, 2007). The transfer of energy up to other trophic levels through the consumption of cultured bivalves by small fish is considerably weaker than the transfer of energy through zooplankton. Fish and particularly larvae that rely on high concentrations of zooplankton may starve (Gibbs, 2007).

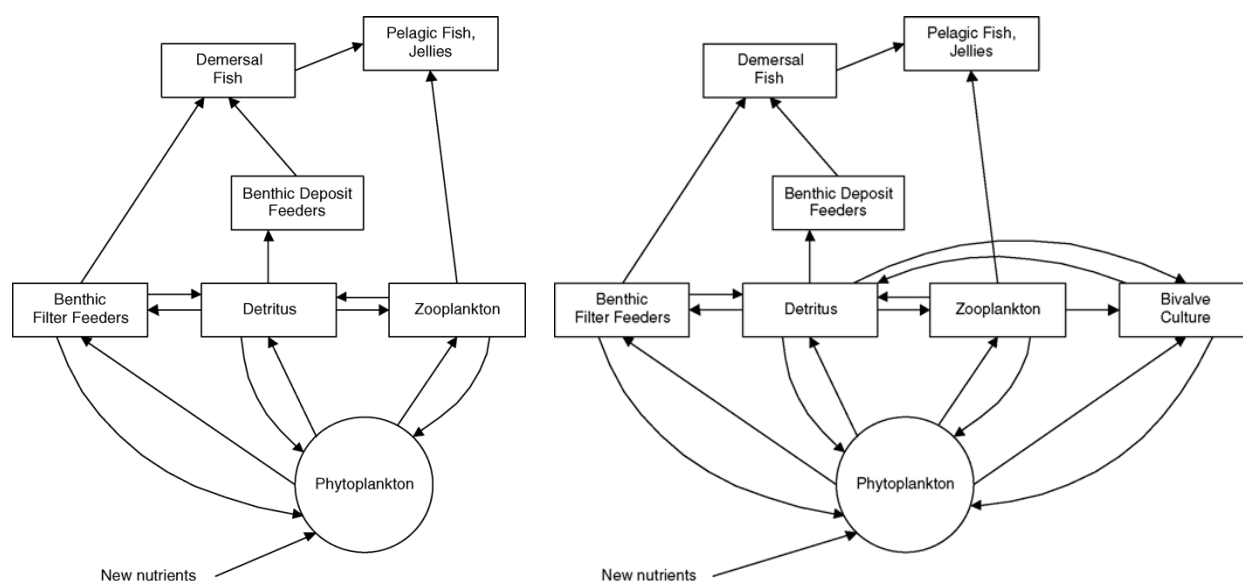


Figure 5. Theoretical food web in area where bivalve culture is performed prior to the introduction of farms (left) and where bivalve culture is included (right). Arrows represent flow of energy (carbon) through the web and only the major energy pathways are shown (from Gibbs, 2007).

Jiang and Gibbs (2005) used food web modelling to explore how changes in bivalve biomass affect energy fluxes occurring within a bay, and the resulting impacts on the biomass of other groups in the system. They predicted that the introduction of large-scale bivalve culture would decrease the mean trophic level of the ecosystem and that a significant change in the structure of the food web can occur at relatively low culture intensity (20% of the systems production carrying capacity). These authors also stated "...it is also reasonable to expect that as the system collapses down to a system dominated by the bivalve monoculture, the resilience may decrease and the system may become more susceptible to disease or biological invasions that may reduce the yield performance of the culture."

Summary of possible consequences to wild fish from food-web interactions with bivalve mariculture:

- Bivalve mariculture has the capacity, under some conditions, to control phytoplankton size-structure, biomass and production through a combination of top-down (grazing pressure) and bottom-up (nutrient availability) environmental interactions.
 - As bivalve control over the phytoplankton increases through increased stocking, a point will be reached where stimulatory effects on primary production from enhanced nutrient regeneration become overshadowed by grazing pressure, and primary production will begin to decrease.
 - Food web interactions with bivalve aquaculture also include a reduction or replacement of the role of zooplankton, shifts in pelagic and benthic communities and alteration of the microbial loop.
 - Large-scale depletion of microorganisms and detritus by bivalves exerts pressure on native filter-feeder species (including commercial shellfish) to maintain natural levels of production.
 - The predicted food web effects of bivalve mariculture, based on ecosystem modelling, include a reduction in the number of trophic levels even when the cultured stock is below sustainable aquaculture production levels (production carrying capacity).
 - The consequences of bivalve-induced changes in marine food webs on fin-fish stocks are not well understood, are difficult to quantify, and there is little conclusive evidence of causal relationships. However, there are reasonable grounds to anticipate effects in some coastal areas supporting intensive bivalve mariculture activities.
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References

- Bacher C., Duarte P., Ferreira J.G., Héral M., Raillard O. 1998. Assessment and comparison of the Marennes-Oléron Bay (France) and Carlingford Lough (Ireland) Carrying Capacity with ecosystem models. *Aquatic Ecol.* 31:379–94.
- Bacher C., Grant J., Hawkins A., Fang J., Zhu P., Duarte P. 2003. Modeling the effect of food depletion on scallop growth in Sungo Bay (China). *Aquat. Living Resour.* 16, 10-24.
- Blanco, J., Zapata, M., Morono, A. 1996. Some aspects of the water flow through mussel rafts. *Sci. Marina.* 60, 275–282.
- Boyd, A.J. and K.G. Heasman. 1998. Shellfish mariculture in the Benguela system: water flow patterns within a mussel farm in Saldanha Bay, South Africa. *J. Shellfish Res.* 17: 25-32.
- Caroppo, C. The contribution of picophytoplankton to community structure in a Mediterranean brackish environment. *J. Plankton Res.* 22: 387-397.
- Cloern, J.E. 1982. Does the benthos control phytoplankton biomass in southern San Francisco Bay? *Mar. Ecol. Prog. Ser.* 9, 191-202.
- Chapelle A., Ménesguen A., Deslous-Paoli J.M., Souchu P., Mazouni N., Vaquer A., Millet B. 2000. Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed. *Ecol Model* 127:161–81.

- Courties C., Vaquer A., Lautier J., Troussellier M., Chrétiennot-Dinet M.J., Neveux J., Machado C., Claustre H. 1994. Smallest eukaryotic organism. *Nature* 370:255
- Cranford, P.J., Strain, P.M., Dowd, M., Hargrave, B.T., Grant, J., Archambault, M.-C. 2007. Influence of mussel aquaculture on nitrogen dynamics in a nutrient enriched coastal embayment. *Mar. Ecol. Prog. Ser.* 347, 61-78.
- Cranford, P.J., Li, W., Strand, Ø., Strohmeier, T. 2008. Phytoplankton depletion by mussel aquaculture: high resolution mapping, ecosystem modeling and potential indicators of ecological carrying capacity. ICES CM 2008/H:12. International Council for the Exploration of the Sea, Copenhagen.
- Cranford, P.J., Ward, J.E., Shumway, S.E., 2011. Bivalve filter feeding, variability and limits of the aquaculture biofilter. In: Shumway, S.E. (Ed.), *Shellfish Aquaculture and the Environment*, John Wiley & Sons, Inc, Chichester, UK, pp. 81-112.
- Dame, R.F., 1996. *Ecology of Marine Bivalves. An Ecosystem Approach*. CRC Press, Boca Raton.
- Dame, R.F., Prins, T.C. 1998. Bivalve carrying capacity in coastal ecosystems. *Aquat. Ecol.*, 31, 409–421.
- Davenport, J., R.J.J.W. Smith, M. Packer. 2000. Mussels *Mytilus edulis*: significant consumers and destroyers of mesozooplankton. *Mar. Ecol. Prog. Ser.* 198 (2000), pp. 131–137
- Doering, P.H., Oviatt, C.A. 1986. Application of filtration rate models to field populations of bivalves: an assessment using experimental mesocosms. *Mar. Ecol. Prog. Ser.* 31, 265–275.
- Dowd, M. 2003. Seston dynamics in a tidal inlet with shellfish aquaculture: a model study using tracer equations. *Estuar. Coast. Shelf Sci.* 57, 523-537.
- Dowd M. 2005. A biophysical model for assessing environmental effects of marine bivalve aquaculture. *Ecol Model* 183: 323-346
- Duarte, O., Labarta, U., Fernández-Reiriz, M.J. 2008. Modelling local food depletion effects in mussel rafts of Galician Rias. *Aquaculture* 274, 300-312.
- Dupuy, C., Le Gall S., Hartmann H.J., Bréret M. 1999. Retention of ciliates and flagellates by the oyster *Crassostrea gigas* in French Atlantic coastal ponds: protists as a trophic link between bacterioplankton and benthic suspension-feeders. *Mar Ecol Prog Ser* 177:165–175
- Dupuy, C., Vaquer A., Lam H.T., Rougier C., Mazouni N., Lautier J., Collos Y., Le Gall S. 2000. Feeding rate of the oyster *Crassostrea gigas* in a natural planktonic community of the Mediterranean Thau Lagoon. *Mar. Ecol. Prog. Ser.* 205: 171-184.
- Ferreira, J., Hawkins, A.J.S., Bricker, S.B., 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model. *Aquaculture* 264, 160-174.
- Ferreira J, Duarte P, Ball B. 1998. Trophic capacity of Carlingford Lough for aquaculture—analysis by ecological modelling. *Aquatic Ecol* 31:361–79.
- Filgueira, R. and J. Grant. 2009. A box model for ecosystem-level management of mussel carrying capacity in a coastal bay. *Ecosystems* 12: 1222-1233.
- Gibbs, M.T. 2007. Sustainability performance indicators for suspended bivalve aquaculture activities. *Ecol. Indic.* 7, 94–107.
- Granéli, E., Olsson, P., Carlsson, P., Graneli, W., and Nylander, C. 1993. Weak 'top-down' control of dinoflagellate growth in the coastal Skagerrak. *J. Plankton Res.* 15: 213-237.
- Grant, J., Filgueira, R. 2011. The application of dynamic modeling to prediction of production carrying capacity in shellfish farming, pp. 135-151. In: Shumway, S.E. (Ed.), *Shellfish aquaculture and the environment*. John Wiley and Sons, Inc., Chichester, UK.
- Grant, J., Bugden, G., Horne, E., Archambault, M.C., Carreau, M. 2007. Remote sensing of particle depletion by coastal suspension-feeders. *Can. J. Fish. Aquat. Sci.* 64, 387–390

- Grant, J., Bacher, C., Cranford, P.J., Guyondet, T., Carreau, M. 2008. A spatially explicit ecosystem model of seston depletion in dense mussel culture. *J. Mar. Syst.* 73, 155–168.
- Heasman, K.G., Pitcher, G.C., McQuaid, C.D., Hecht, T. 1998. Shellfish mariculture in the Benguela system: raft culture of *Mytilus galloprovincialis* and the effect of rope spacing on food extraction, growth rate, production, and condition of mussels. *J. Shellfish Res.* 17, 33–39.
- Heral, M. 1993. Why carrying capacity models are useful tools for management of bivalve molluscs culture. In: Dame R, Ed. *Bivalve filter-feeders in estuarine and coastal ecosystems*. New York: Springer-Verlag. p 455–77.
- Jiang, W., and M.T. Gibbs. 2005. Predicting the carrying capacity of bivalve shellfish culture using a steady, linear food web model. *Aquaculture* 244: 171–185.
- Klaveness D. 1990 Size structure and potential food value of the plankton community to *Ostrea edulis* L. in a traditional Norwegian 'Østerspoil'. *Aquaculture* 86, 231–247.
- Lehane, C., Davenport, J., 2006. A 15-month study of zooplankton ingestion by farmed mussels (*Mytilus edulis*) in Bantry Bay, Southwest Ireland. *Est. Coast. Shelf Sci.* 67, 645–652.
- Lindahl, O. 2011. Mussel farming as a tool for re-eutrophication of coastal waters: experiences from Sweden. In: Shumway, S.E. (Ed.), *Shellfish Aquaculture and the Environment*, Jon Wiley & Sons, Inc, Chichester, UK, pp. 217–237.
- Maar M., Nielsen, T.G., Bolding, K., Burchard, H., Visser, A.W. 2007. Grazing effects of blue mussel *Mytilus edulis* on the pelagic food web under different turbulence conditions *MEPS* 339:199–213
- Maar, M., Nielsen, T.G., Petersen J.K., 2008. Depletion of plankton in a raft culture of *Mytilus galloprovincialis* in Ria de Vigo, NW Spain. II. Zooplankton. *Aquat. Biol.* 3, 127–141.
- McKindsey, C.W., Thetmeyer, H., Landry, T., Silvert, W., 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture*. 261: 451–462.
- Møhlenberg, F., Riisgård, H. U., 1978. Efficiency of particle retention in 13 species of suspension feeding bivalves. *Ophelia*, 17, 239–246.
- Newell, R.I.E. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. *J. Shellfish Res.* 23, 51–61.
- Nielsen TG, Maar M. 2007. Effects of a blue mussel *Mytilus edulis* bed on vertical distribution and composition of the pelagic food web. *Mar Ecol Prog Ser* 339:185–198
- Norén, F., J. Haamer and O. Lindahl. 1999. Changes in the plankton community passing a *Mytilus edulis* mussel bed. *Mar. Ecol. Prog. Ser.* 191: 187–194.
- Ogilvie, S.C., Ross, A.H., Schiel, D.R. 2000. Phytoplankton biomass associated with mussel farms in Beatrix Bay, New Zealand. *Aquaculture* 181, 71–80.
- Olsson, P., Graneli, E., Carlsson, P., Abreu, P. 1992. Structure of a post spring phytoplankton community by manipulation of trophic interactions. *J. Exp. Mar. Biol. Ecol.* 158, 249–266.
- Petersen, J.K., Nielsen, T.G., van Duren, L., Maar, M. 2008. Depletion of plankton in a raft culture of *Mytilus galloprovincialis* in Ria de Vigo, NW Spain. I. Phytoplankton. *Aquat. Biol.* 4, 113–125.
- Raillard O, Ménesguen A. 1994. An ecosystem model for the estimating the carrying capacity of a macrotidal shellfish system. *Mar Ecol Prog Ser* 115:117–30.
- Riemann, B., Nielsen, T. G., Horsted, S. J., Bjernsen, P. K. Pock-Steen J. (1988). Regulation of phytoplankton biomass in estuarine enclosures. *Mar. Ecol. Prog. Ser.* 48: 205–215
- Souchu, P., Vaquer, A., Collos, Y., Landrein, S., Deslous-Paoli, J.-M., Bibent, B. 2001. Influence of shellfish farming activities on the biogeochemical composition of the water column in Thau lagoon. *Mar. Ecol. Prog. Ser.* 218: 141–152

- Smaal A., Stralen M., Schuiling E. 2001. The interaction between shellfish culture and ecosystem processes. *Can J Fish Aquat Sci* 58:991–1002.
- Smaal, A.C., Schellekens, T., van Stralen, M.R., Kromkamp, J.C. 2013. Decrease of the carrying capacity of the Oosterschelde estuary (SW Delta, NL) for bivalve filter feeders due to overgrazing? *Aquaculture* 404-405, 28-34.
- Stockner, J.G. 1988. Phototrophic picoplankton: and overview from marine and freshwater ecosystems. *Limnol. Oceanogr.* 33: 765-775.
- Stoecker D.K., Capuzzo J.M.D. 1990. Predation on protozoa: its importance to zooplankton. *J Plankton Res* 12:891–908
- Strohmeier, T., Aure, J., Duinker, A., Castberg, T., Svoldal, A., Strand, Ø. 2005. Flow reduction, seston depletion, meat content and distribution of diarrhetic shellfish toxins in a long-line mussel (*Mytilus edulis*) farm. *J Shellfish Res.*, 24,15–23.
- Trottet, A., Roy, S., Tamigneaux, E., Lovejoy, C., Tremblay, R., 2008. Influence of suspended mussel farming on planktonic communities in Grande-Entrée Lagoon, Magdalen Islands (Québec, Canada). *Aquaculture* 276, 91-102.
- Vaquer, A., Troussellier, M., Courties, C., Bibent, B., 1996. Standing stock and dynamics of picophytoplankton in the Thau Lagoon (Northwest Mediterranean Coast). *Limnol. Oceanogr.* 41, 1821-1828.
- Ward, J. E. and S. E. Shumway (2004) Separating the grain from the chaff: particle selection in suspension- and deposit-feeding bivalves. *Journal of Experimental Marine Biology and Ecology* 300: 83-130
- Zeldis, J., K. Robinson, A. Ross and B. Hayden. 2004 First observations of predation by New Zealand Greenshell mussels (*Perna canaliculus*) on zooplankton. *Journal of Experimental Marine Biology and Ecology* 311: 287-299.

5 Priority Mariculture Pressures on Wild Fish

The above overviews of current science knowledge provide information on a multitude of mariculture pressures that interact, to varying degrees, with wild fish. The OSPAR (EIHA) proposal that ICES identify pressures having sufficient documentation regarding their impacts to implement management measures resulted in considerable debate within WGAQUA on how best to arrive at these conclusions. A number of hazard and risk identification and assessment approaches were considered that utilize the available science knowledge to provide advice on the probability and consequences of a hazard occurring, and the degree of uncertainty involved. However, the WGAQUA ultimately concluded:

“It is not feasible to reach generic conclusions on aquaculture interactions with wild fish that are applicable across the full ICES or OSPAR regions. Consequently, it is also not feasible to identify and prioritize major mariculture pressures at the geographic scale identified.”

Aquaculture activities are highly diverse and impacts on wild fish may be expected to be highly site-specific. Management initiatives therefore need to target pressures interacting at an appropriate national, regional or farm-level. Addressing the OSPAR request requires regional considerations that cannot be fully investigated or integrated within this rapid science response. However, the information provided in this document is meant to contribute to continuing efforts to improve regional mariculture management approaches and tools that are both knowledge- and ecosystem-based.

Recommendation to ACOM: The WGAQUA has been promoting our role in providing advice to clients on a wide range of aquaculture issues. This OSPAR advice request targets an extremely wide-ranging topic that is applicable to a broad range of mariculture activities in a multitude of environmental settings (most ICES member countries). Such a large generic advisory request greatly diluted the capacity of WGAQUA to provide advice in a form that can be easily interpreted and utilized by clients. It is recommended that ICES communicate with OSPAR and other clients the need to focus future questions on individual aquaculture pathways-of-effect (e.g. sea lice, escapes, organic wastes, etc.) for specific culture species, and for particular regional seas.

6. Approaches to Mariculture Management

Mariculture environment interactions are currently managed within ICES member countries and risk and impact management approaches have been implemented to address the specific requirements of the area in question. The details of these programs are available from the appropriate agencies and are not repeated herein, with the exception of providing an example based on the Norwegian risk assessment approach. The following sections are provided of examples of a wide range of available methods intended to prevent or mitigate specific mariculture pressures on the marine environment, including impacts on wild fish and shellfish.

6.1 ICES Code of Practice on Introduction and Transfer of Marine Organisms, 2005

A code of practice was developed for marine aquaculture activities and outlines a consistent, transparent process for the evaluation of a proposed new introduction, including detailed biological background information and an evaluation of risks (ICES. 2005. ICES Code of Practice on the Introductions and Transfers of Marine Organisms 2005. 30 pp.). Some general considerations provided regarding interactions between native and some mariculture species include:

- “Recognizing that little information still exists on the genetic, ecological, and other effects of the release of genetically modified organisms into the natural environment (where such releases may result in the mixing of altered and wild populations of the same species, and in changes to the environment), the Council urges Member Countries to establish strong legal measures to regulate such releases, including the mandatory licensing of physical or juridical persons engaged in genetically modifying, or in importing, using, or releasing any genetically modified organism.”
- “The technology now exists to allow the production of triploid and tetraploid fish and shellfish (polyploid) in commercial quantities. However, little information exists on the genetic, ecological, and other effects of the release of polyploid organisms into the natural environment (where such releases may result in the mixing of altered and wild populations of the same species, hybridization between species, and in changes to the environment).” “The mass releases of sterile organisms could still negatively impact the ecosystem and affect wild populations through competition.”

6.2 Norwegian risk assessment

The Norwegian risk assessment of fish farming activity deals with a variety of documented and potential hazards and impacts on wild populations and the environment

(Taranger *et al.*, 2011, 2014, submitted). The risk assessment builds on the goals specified by the Norwegian Government in the report “Strategy for an environmentally sustainable Norwegian Aquaculture Industry” (Anon., 2009):

Goal 1: Disease	Disease in fish farming will not have a regulating effect on stocks of wild fish, and as many farmed fish as possible will grow to slaughter age with minimal use of medicines.
Goal 2: Genetic interaction	Aquaculture will not contribute to permanent changes in the genetic characteristics of wild fish stocks.
Goal 3: Pollution and discharge	All fish farming locations in use will maintain an acceptable environmental state, and will not have higher emissions of nutrient salts and organic materials than the receiving waters can tolerate.
Goal 4: Zoning	The aquaculture industry will have a location structure and zoning which reduces impact on the environment and the risk of infection.
Goal 5: Feed and feed resources	The aquaculture industry’s needs for raw materials for feed will be met without over-exploitation of wild marine resources.

The most current report (Taranger *et al.*, 2014) covers factors where most impact studies and monitoring data are available; introgression of escaped farmed salmon into wild populations, impact of salmon lice on wild salmonid populations, potential disease transfer from farmed salmon to wild salmonid populations, local and regional impacts of organic load and nutrients from marine salmon farms, and fish welfare.

References

- Anon. 2009. Strategy for an Environmentally Sustainable Norwegian Aquaculture Industry. The Norwegian Ministry of Fisheries and Coastal Affairs (<http://www.regjeringen.no/en/dep/fkd/Documents/reports-and-plans/plans/planer-og-strategier-2009/strategy-for-an-environmentally-sustaina.html?id=566395>).
- Taranger, G. L., Boxaspen, K. K., Madhun, A. S., Svåsand, T., and (eds.) 2011. Risk assessment – environmental impacts of Norwegian aquaculture. Extracts from “Fisken og havet, 3-2010”, Printed August 2011, Institute of Marine Research, Norway.
- Taranger, G. L., Svåsand, T., Kvamme, B. O., Kristiansen, T. S., Boxaspen, K. K., and (red.) 2014. Risk assesment of Norwegian aquaculture 2013 [Risikovurdering norsk fiskeoppdrett 2013] (in Norwegian). Fisken og Havet, Særnummer 2-2014.

6.3 Industry Best Practices and Aquaculture Certification

The concept of Best Management Practices (BAPs) was originally developed for a wide range of industries to reduce costs and increase production efficiencies. BAPs evolved as a means to also improve environmental management and performance. Aquaculture farm-specific BMP manuals are in use in many areas and these individual farm environmental management plans are intended to contribute to the responsible management of the farm. BAPs have been incorporated as part of a wide range of aquaculture Certification and Ecolabel programs, which imply that certified producers are more environmentally responsible than uncertified producers. The following description of aquaculture certification programs and their contributions as a market-based approach to environmental effects management was extracted, largely verbatim, from a recent ICES WGMASC review (Cranford *et al.* 2012) and the cited papers are available in that publication.

The creation of certification schemes based on performance-based standards is designed to manage key environmental issues associated with mariculture. It is believed that the implementation of certification schemes will help the industry sector to work toward more sustainable aquaculture, including reduced impacts. The underlining principle of certification is that a fully independent body from the production sector should be responsible for certification while the costs are borne by industry. Certification schemes relevant in some way to aquaculture have been reviewed by Funge-Smith *et al.* (2007) and the World Wildlife Fund (WWF 2007). Organisations active in this field include the FAO, ISO, Aquaculture Stewardship Council, Friends of the Sea, Naturland, Global Gap, and the Aquaculture Certification Council. The Marine Stewardship Council decided to cease working on aquaculture certification, but continues to be a key participant because it does certify aquaculture activities where juveniles are collected from wild stocks.

A shortcoming in addressing bivalve aquaculture sustainability issues through a market-driven certification approach is that consumer awareness and values related to environmental impacts varies towards both extremes across and within geographic markets. Local perceptions on the acceptability of aquaculture impacts may not match more broadly established environmental quality criteria enforced by regulatory agencies. Another potential limitation of certification schemes is that they currently do not fully encompass the complexities of interactions between aquaculture and the ecosystem and therefore do not meet criteria outlined in legislations that mandate an ecosystem approach. Third-party certification schemes do not, and are not meant to, displace an effective governance approach for ensuring the sustainable use of coastal ecosystems. A key benefit to the underlying work that has gone into the establishment of certification schemes is the compilation of information on societal expectations on the ecological performance of aquaculture operations. For example, the WWF aquaculture certification standards (transferred to the Aquaculture Stewardship Council) were developed based on wide stakeholder participation in multiple dialogue workshops and through open calls for comments on the draft performance-based standards. This participatory multi-stakeholder approach, which included science input at all stages, was an iterative process designed to both reveal and balance opposing views.

Reference

Cranford P.J., Kamermans P., Krause G., Mazurié J., Buck B., Dolmer P., Fraser D., Gubbins M., Van Nieuwenhove K., O'Beirn F.X., Sanchez-Mata A., Thorarinsdóttir G.G., Strand Ø. 2012. An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts. *Aquacult. Environ. Interac.* 2: 193-213.)

6.4 Extractive Aquaculture

Eutrophication due to excess levels of nitrogen and phosphorus in estuaries and coastal waters is a serious global problem (Cloern, 2001) that can result in drastic negative changes in fisheries productivity, species richness and the composition of fish assemblages (Caddy, 1993). Although aquaculture can result in some degree of eutrophication of the surrounding environment, suspended mussel aquaculture is being promoted as a possible mitigation measure for improving coastal water quality (e.g. Lindahl, 2005). Mussels live in dense populations and filter large volumes of water to capture phytoplankton and other suspended particulate matter (see above). Mussels generally grow fast under eutrophic conditions resulting in the bio-concentration of nitrogen and phosphorus in mussel meat. The removal of excess nu-

trients from coastal waters during the mussel harvest reduces the occurrence and magnitude of algal blooms and is therefore a possible eco-engineering approach for combating eutrophication (Lindahl, 2005). This concept of extraction culture using mussels was tested on the Swedish West coast, where it was implemented as compensation for continued emission of nitrogen from a local sewage plant. The concept is also being studied at a commercial-scale, experimental mussel farm in the Limfjorden, Denmark.

Integrated Multi-Trophic Aquaculture (IMTA) systems also rely on the use of extractive species for mitigating impacts related to organic and inorganic waste releases from finfish aquaculture. Waste usage efficiencies of candidate extractive species (filter- and deposit-feeders and marine plants) have been well studied and indicate that many commercial species have a high potential for waste bioremediation. One of the greatest challenges to the development of efficient open-water IMTA systems has been to maximize waste capture in these dynamic coastal systems. Effective waste bioremediation requires the extractive species to be exposed to all waste transport pathways and for a sufficient time to allow uptake of the waste before it is transported away from the IMTA system. A quantitative assessment of the capacity of mussels, the most commonly utilized organic waste extraction species, to capture and remove organic fish wastes from the water column indicated that intensive (high biomass) and spatially extensive IMTA systems are needed to extract a small fraction of the organic waste available (Cranford *et al.* 2013). Similar results were reported for the removal of inorganic wastes by seaweeds (Troell *et al.* 2009).

A 2013 workshop discussion facilitated by the Canadian IMTA Network (CIMTAN), reached the following conclusions on the potential of shellfish filter-feeders to mitigate organic wastes within open-water IMTA systems (P. Cranford, personal communication):

- a) Shellfish filter-feeders can utilize and benefit from the additional presence of organic fish waste (OFW) in the natural seston food supply.
- b) The enhancement of particulate food supply availability in waters adjacent to open-water fish-pens from OFW production is highly localized (generally less than 10 m from the net-pens) and of low magnitude (generally less than 1 mg L⁻¹). Enhancement is highly periodic owing to dispersion, advection and mixing processes in open-water conditions, and farm management practices. There is no evidence of a continuous horizontal plume of OFW emanating from open-water fish net-pens.
- c) The vertical flux of OFW is much greater than the horizontal flux owing to fish faeces dominating the total OFW production and the rapid settling of faeces relative to waste feed fines.
- d) Shellfish growth enhancement from OFW consumption generally occurs under conditions of natural food supply limitation, such as in oligotrophic (i.e. low phytoplankton) areas, during seasons of low food availability (e.g. winter) and at sites where the nutritional value (quality for shellfish growth) of the seston is naturally low. Consequently, shellfish growth enhancement from OFW at typical IMTA sites in Canada may be expected to be low and limited primarily to the winter.
- e) A number of known factors severely limit the capacity of filter-feeders to capture and extract the vertical and horizontal flux of OFW, including (1) the

rapid passage of OFW past the filter-feeders structures (time constraint) and (2) the limited space available to hold a large standing stock of filter-feeders within the farm footprint (space constraint).

Consequently, it was concluded that the utilization of shellfish as an extractive species is not an efficient organic fish waste mitigation measure in open-water IMTA systems. Research is currently being directed more towards the use of benthic filter- and deposit-feeding species to mitigate impacts from the vertical flux of particulate wastes from fish net-pens.

References

- Caddy, JF 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in fisheries Science*. 1: 57-95.
- Cloern, J, E. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog. Ser.* 210: 223-253.
- Cranford, P.J., S.M.C. Robinson and G. Reid. 2013. Open Water Integrated Multi-Trophic Aquaculture: Constraints on the Effectiveness of Mussels as an Organic Extractive Component. *Aquacul. Envir. Interact.* 4: 163-171.
- Lindahl, O., R. Hart, B. Hernroth, S. Kollberg, L.-O. Loo, L. Olrog, A.-S. Rehnstam-Holm, J. Svensson, S. Svensson, and U. Syversen. 2005. Improving Marine Water Quality by Mussel Farming: A Profitable Solution for Swedish Society. *A Journal of the Human Environment*. 34(2):131-138.
- Troell, M., Al. Joyce., T. Chopin, A Neori, A.H. Buschmann, and J.-G. Fang. 2009. Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297:1-9.

Annex 4: Emerging issues

Table I. Emerging and relevant issues sorted by thematic group as defined by EATiP and topics addressed in the WGAQUA group discussion in 2013.

Thematic groups suggested by EATiP	Central topics defined by WGAQUA
Integration with the Environment	<ul style="list-style-type: none"> • Benthic impacts • Introduction of new species and transfer of species between countries • Interaction of escapees with natural environment (<i>genetic</i>, ecological) • Ecological carrying capacity • Introduction of hard substrate/ structures • Capture based aquaculture • Interaction with wild populations/species
Technology & Systems	<ul style="list-style-type: none"> • Off shore (exposed) • Land based, RAS • Prevent escapees • Enclosed systems (e.g. sea cages) • IMTA, nutrient trading, upwelling • Juvenile supply • Production practice • Macroalgae production • Pest management (biofouling and predator control)
Product quality, Consumer Safety & Health	<ul style="list-style-type: none"> • Traceability (<i>genetic</i>, farm to fork and fork to farm) • Different feed (organoleptic, fish quality/taste, health value, fish health) • Functional food (omega 3)
Managing the Biological Lifecycle	<ul style="list-style-type: none"> • Domestication • Improving yield of hatcheries • Juvenile quality • Optimising production cycle
Sustainable Feed Production	<ul style="list-style-type: none"> • Feed sources (how to use available sources or produce feed for fish – mussels/macroalgae/single cell proteins/invasive species/plant)

	<ul style="list-style-type: none"> production) • GMO (soymeal supply) • Phytoplankton production (feed, bio-fuel?)
Knowledge Management	<ul style="list-style-type: none"> • Tools to make scientific and technological knowledge available to managers and industry
Aquatic Animal Health & Welfare	<ul style="list-style-type: none"> • Pest management (sea lice) • Fish welfare

Table II. Emerging and relevant issues suited to be addressed by other groups within ICES.

Topic	ICES group suggested to take on this topic
Socio economics (externalities, viability, coastal communities, food security)	SGSA
Microplastics	Mar Chem
Climate change	Several groups
Disease, probiotics, vaccine development, medicines	WGPDMO
Marine spatial planning (combinations?, zonation ICZM, spatial scale)	WGMPCZM
Hydrodynamic modelling (currents, waves) oceanographic EG, tidal energy group	ecosystem groups
Natural dynamic condition (time scale)	
Harmful algal blooms	WGHABD
Transport (well boat, pest management)	WGITMO WG Ballast water
Statistical and analytical methods for quantifying genetic introgression of farmed escaped salmon in native populations	WGAGFM

Socio-economics, Management & Governance

- Market (development, segmentation, differentiation, branding)
- Educated consumer
- Training aquaculture people

- Monitoring program (indicators and thresholds)
- Risk assessment
- Need for regulations, EU directives, licencing (space, time, environment)
EATiP
- Standards
- Carrying capacity
- Marine spatial planning of aquaculture (combinations?, zonation ICZM, spatial scale) joint meeting with WGMPCZM

Annex 5: Technical minutes from the Review Group “Interaction between Wild and Captured Fish Stocks” (RGFISH)

1. Special request: Interactions between wild and captive fish stocks (OSPAR 4/2014)

- a) Recalling the conclusion of the QSR 2010 that mariculture is a growing activity in the OSPAR maritime area, EIHA 2012 considered the potential for increasing environmental pressure relating to the growth of this industry. As yet this is not an established work stream within EIHA, and Contracting Parties have requested that more information be brought forwards on this issue. This was reiterated by EIHA 2013.
- b) Mariculture has a number of associated environmental pressures such as the introduction of non-indigenous species, which can have ecological and genetic impacts on marine environment and especially on wild fish stocks; in addition, pressures from mariculture might include:
 - i) introduction of antibiotics and other pharmaceuticals;
 - ii) transfer of disease and parasite interactions;
 - iii) release of nutrients and organic matters;
 - iv) introgression of foreign genes, from both hatchery-reared fish and genetically modified fish and invertebrates, in wild populations;
 - v) effects on small cetaceans, such as the bottlenose dolphin, due to their interaction with aquaculture cages.
- c) EIHA proposes that OSPAR requests ICES to provide:
 - i) an update on the available knowledge of these issues;
 - ii) concrete examples of management solutions to mitigate these pressures on the marine environment;
 - iii) advice on which pressures have sufficient documentation regarding their impacts to implement relevant monitoring and suggest a way forward to manage these pressures.
- d) It may be appropriate to explore cooperation with other competent authorities working in this field, such as the European Food Safety Authority with respect to disease transfer or parasites, or the North Atlantic Salmon Conservation Organisation (NASCO), in particular with respect to existing cooperation between NASCO and ICES on issues pertaining to pressures from mariculture.

2. Technical Minutes from the Review Group Interaction between Wild and Captured Fish Stocks (RGFISH)

- RGFISH
- Review deadline 17 June 2014
- Peer Reviewers: Luc Comeau (Canada); Edmund Peeler (UK); Ellen Kenchington (Canada; RG Chair)
- Working Group: WGAQUA

2.1. WGAQUA Summary

WGAQUA contributed information on the pressures to wild fish from several mariculture activities (introduction of antibiotics and other pharmaceuticals; parasite interactions; non-genetic interactions from mass releases of cultured organisms including fish escapes and bivalve transfers/spawning; release of nutrients and organic matter; addition of structure/habitat by bivalve culture, and utilization of trophic resources by mariculture). The report provides an update on the available knowledge on these aquaculture pressures and some examples of management solutions to mitigate these pressures on the marine environment. Aquaculture activities in the ICES and OSPAR regions are highly diverse and impacts on wild fish may be expected to be highly site-specific. Consequently, it was not possible for WGAQUA to reach generic conclusions on aquaculture interactions with wild fish, or to identify and prioritize major mariculture pressures that are applicable across the full ICES or OSPAR regions.

2.2. Review of Annex 3: OSPAR Science Advise Request (2013/4)

WGAQUA address the potential interactions outlined in paragraph b. i), ii) and iii) of the OSPAR Request (Section 1 above) i.e., introduction of antibiotics and other pharmaceuticals; transfer of disease and parasite interactions; release of nutrients and organic matters. They also considered three other interactions not referred to in the Request but thought to be relevant: non-genetic interactions from mass releases of cultured organisms (fish escapes and bivalve transfers/spawning); addition of structure/habitat by bivalve culture, and utilization of trophic resources by mariculture. RGFISH considers that the WGAQUA report effectively summarizes available knowledge relating to those interactions with some sections being more effectively covered than others (see specific comments below). Given the broad range of topics addressed this is a considerable achievement and the WG members are to be congratulated on their efforts. However, the report does not answer the request and the WGAQUA explicitly recognizes that outcome. It is particularly weak on addressing paragraph c. of the Request:

- ii) concrete examples of management solutions to mitigate these pressures on the marine environment;
- iii) advice on which pressures have sufficient documentation regarding their impacts to implement relevant monitoring and suggest a way forward to manage these pressures.

While RGFISH accepts that case-specific evaluations are needed in most cases, there are a few examples where there may be sufficient data to effectively mitigate and monitor impacts using generic measures.

RGFISH noted:

4.1. Wild fish interactions with mass releases of cultured organisms

4.1.1. Movement of shellfish

This section has clearly been authored by a number of scientists. It lacks coherence and would benefit from sub-headings. It is self-evident that the movement of infected live animals will result in disease spread and the report needs to explore the issue of whether adverse population level effects have resulted.

The summary provided in WGAQUA Table 1 (their section 3) seems a bit misleading for bivalve molluscs. The word “pressure” although reflecting the use of the client, has a negative connotation, and in this case implies that bivalve farming activities have a negative impact on wild fish. Yet the report concludes that “The consequences of bivalve-induced changes in marine food webs on fin-fish stocks are not well understood, are difficult to quantify, and there is little conclusive evidence of causal relationships.” Perhaps the heading “Pressure on wild fish” in Table 1 should be replaced with something along the lines of “aquaculture pathways-of-effect”. Also, “habitat formation”, “organic wastes” (elsewhere defined as “seabed organic enrichment”), and “ecological services” should be categorized as having potential positive effects. “Ecological services” should be explicitly defined as improving water clarity, increasing light penetration, and mitigating anthropogenic nutrient loading. In summary the format of Table 1 (part on bivalve molluscs) implicitly announces that bivalve aquaculture negatively impacts wild fish stocks, a conclusion that is not supported by the report.

With regards to the paragraph describing Table 1, and more specifically the positive effects on biodiversity and productivity, WGAQUA may wish to consider adding bioremediation to counter anthropogenic nutrient loading in coastal areas. This information appears deeper in the document, but it should be added to the paragraph describing Table 1. Also, the following references could be added for the topic of bioremediation:

Carmichael, R.H., Walton, W., and H. Clark ,2012. Bivalve-enhanced nitrogen removal from coastal estuaries. *Canadian Journal of Fisheries and Aquatic Sciences* 69:1131-1149.

Higgins, C.B., K. Stephenson, and B.L. Brown, 2011. Nutrient bioassimilation capacity of aquacultured oysters: quantification of an ecosystem service. *Journal of Environmental Quality* 40:271-277.

Lindahl, O., 2011. Mussel farming as a tool for re-eutrophication of coastal waters: experiences from Sweden. *Shellfish aquaculture and the environment*. S. E. Shumway, Wiley-Blackwell, pages 217-237.

RGFISH concluded that the examples in Table 1 would be more informative if written as case studies. For example, the impact of Pacific oysters in regions where they have been introduced-including the development of self-sustaining wild populations which have altered local ecosystems- would be a good case study.

The report correctly states that it is not possible to draw clear conclusions about interaction between wild and farmed shellfish. The evidence base needs to be explored in more detail. For example, is there any evidence of declines in harvests of managed

shellfish in areas where farmed shellfish have suffered disease outbreaks? Does the evidence base exist to make this judgement? For example, are there any reports or investigations of disease in wild shellfish following epidemics (e.g. OsHV1) in farmed shellfish?

Concrete examples of mitigation measures [paragraph c. ii) of the OSPAR Request] relating to the transfer of bivalves are reportedly identified in Table 2. However, an inspection of Table 2 revealed no example of such measures. This table is confusing and does not appear particularly useful. Some explanation for the column headings may help. It appears that the only robust conclusion regarding mitigation is the following: “the utilization of shellfish as an extractive species is not an efficient organic fish waste mitigation measure in open-water IMTA systems.”

RGFISH concluded that although there is interesting material in this section of the WGAQUA report, it does not make a significant contribution to knowledge or provide useful recommendations for research or mitigation with respect to the Request.

4.1.2 Escaped fish

RGFISH found that this section of the WGAQUA report provided a thorough and well written summary of the issue. It highlighted the lack of information on environmental impacts of escapees. The conclusion that the impact of predation and competition on other fish stocks is negligible is well argued and sound. The conclusions about impact of escaped salmon on conspecifics, makes good use of the available information and comes to sensible and well-reasoned conclusions. Unfortunately, there is a lack of recommendations on mitigation or future monitoring and research.

4.2. Nutrient and organic matter waste products

RGFISH found that this section of the WGAQUA report provided a thorough and well written summary of the state of knowledge of the issues. In general mitigation measures and monitoring are not discussed.

4.2.1. Bivalve biodeposition and nutrient fluxes

The inclusion of potential impacts on sea grasses and on the importance of bivalve culture to local oxygen and nutrient fluxes is particularly insightful. In particular their conclusion that “the impacts of suspended bivalve culture on benthic infaunal communities are typically limited in magnitude except for under extreme conditions (poor flushing or exceedingly great stocking densities). Responsible husbandry practices may be used to limit these impacts” could be used to address the mitigation aspects of paragraph c of the Request.

4.2.2. Finfish excretion, faeces and waste feed

RGFISH endorses the conclusion that “the degree of enrichment of the environment is dependent on a number of factors including, the size of the farm (i.e. the biomass of fish), the ambient environmental conditions (i.e. hydrodynamics, water depth, wave exposure, topography and substrate type), the husbandry practices at individual fish farms and also the biophysical and biochemical composition of the waste streams”. However there are some mitigating measures that may be useful. RGFISH note that Wu *et al.* (2014) have investigated the flow field around mariculture cages with a three-dimensional hydrodynamic model applied to the Bay of Fundy, Canada. Model results show that the presence of fish cages restricts water flow and damps the velocity in the surface layer occupied by the cages, but enhances the water velocity in the

bottom layer beneath the cages. Their model results also indicate that there exists an optimal drag coefficient and an optimal cage depth for a specific farm site which could be used to mitigate impacts of fish wastes. With the utilization of the optimal drag coefficient and optimal depth, the authors believe that it is possible to speed up the sediment erosion beneath the cages and, thus, decrease the environmental problems caused by accumulated fish farm wastes.

Wu, Y., J. Chaffey, B. Law, D. A. Greenberg, A. Drozdowski, F. Page, and S. Haigh, 2014. A three-dimensional hydrodynamic model for aquaculture: a case study in the Bay of Fundy. *Aquaculture Environment Interactions* Published on line 06/2014; DOI:10.3354/aei00108.

4.3. Addition of physical structure by bivalve mariculture

This section raises an important topic but it is not well developed and could have usefully been expanded to include physical structures of finfish mariculture- drawing distinctions as needed. Aspects of this potential impact are discussed in gear entanglements in the 2014 WGMME report. The report does not mention the impacts of mariculture cages on the local current field and the potential for erosion of the bottom sediment (see reference to Wu et al., 2014 under RGFISH comments on 4.2.2 above).

4.4. Release of antibiotics and other pharmaceuticals

This short section is essentially a review of reviews. It seems to be a reasonable summary, however, there is no attempt to critically assess the papers discussed and the report could benefit from more in-depth analysis of case studies. A conclusion about the impact of antimicrobials etc. is needed and specific recommendations for mitigation.

4.5. Transmission of sea lice and other parasites to wild populations

This is a complicated and controversial subject and deserves a systematic review of the literature to assess whether sea lice impact wild salmonids. This section is a reasonable review of the literature, however, inevitably some important publications seem to have been neglected. For example, Krkošek has published widely on the subject (>10 first author papers) but only one first author paper is reviewed; by contrast 11 first author papers by Jackson are referenced. This suggests an uneven approach to the literature review.

The report should make use of data on the number of farmed salmon put to sea each year compared with returning wild adults in the same region (e.g west coast of Scotland). This information provides some context for the potential impact of farmed salmon as a reservoir of infection.

It is not clear what the authors mean by a 'direct study of sea lice impacting on wild salmon populations in Scotland'. What is a 'direct' study?

The report fails to consider recent evidence that despite control measures, sea lice infestations are not well controlled in Norway, leading to culling. The emergence of resistance to sea lice treatments also is not discussed. There is a serious threat that farmers do not have the necessary tools to control sea lice infestations. This is not properly discussed in this report, nor are mitigation measures suggested.

It is tempting to conclude that only sea lice fall into the category of pressures that have sufficient documentation to implement monitoring. Practices relating to sea lice monitoring and management are summarized for the main ICES salmon producing countries. More specifically, in terms of mitigation and way forward the report states

that “Sea lice are currently controlled by a range of pharmaceuticals, predominantly through the use of, in-feed or bath treatments performed in enclosures in the sea or onboard well boats, but also management practices such as coordinated fallowing, stocking and treatment and cohabitation of cleaner fish as biological control agents.... The development and validation of accurate distribution and abundance models for the dispersion of planktonic lice larvae is needed; this could also be the basis for an area management system based on ‘maximum sustainable lice loads’ or ‘lice quotas.’” These models may provide a way forward to manage the sea lice pressure [paragraph c. iii) of the OSPAR Request]. However, it appears no recommendation has been made since there is no specific mention of sea lice in the WGAQUA Executive Summary.

4.6. Utilization of wild-fish trophic resources by mariculture

4.6.1. Fed culture

This section appears to be a reasonable summary of the current situation however it is based mainly on a recent review and does not fully answer the request. RGFISH notes that the report does not directly consider whether the current exploitation of pelagic stocks for the production of fishmeal is sustainable, or whether the growth of aquaculture can be sustained given increasing human demand for fish oil. Whilst reference is made to declining omega 3 in farmed fish when their diets contain 70% replacement of fish meal with plant protein, the consequences are not fully discussed. Farmed fish are marketed as a health option, this selling point is neutralised if the product contains little omega 3.

4.6.2. Non-fed bivalve culture

RGFISH found that this section of the WGAQUA report provided a comprehensive and well written summary of the state of knowledge of the issues. However, as for other sections of this report mitigation measures and monitoring are not discussed.

RGFISH initially assumed there was sufficient documentation to monitor “marine benthic habitat impacts”, but on this front it seems the WGAQUA agreed to “an outline for a publication on *Assessing and developing tools for monitoring changes in marine benthic habitats associated with aquaculture in the North Atlantic area*”. Also, the rationale for monitoring is presently weak since it is still unclear how benthic impacts are transferred up the food-chain to impact fisheries species.