Strategic overview of influences of aquaculture on biodiversity and ecosystems services in Ireland

Prepared by Myriam Callier[1], Tasman Crowe[1], Dannielle Green[1], Judith Kochmann[1,2], Francis O'Beirn[3] and Gráinne O'Brien[4] as part of SIMBIOSYS, an EPA funded project examining sectoral influences on biodiversity and ecosystem services.

Initial draft completed July 2009,
finalised after consultation December 2011

[1] School of Biology and Environmental Science, Science Centre West, University College Dublin, Belfield, Dublin 4
[2] Graduate Research Education Programme in Sustainable Development, Urban Institute Ireland, University College Dublin, Richview, Dublin 4
[3] Marine Insitute, Rinville, Oranmore, Co. Galway
[4] Bord Iascaigh Mhara, Crofton Road, Dun Laoghaire, Co. Dublin

Key Messages

Aquaculture is a significant industry for Ireland, particularly in remote coastal communities. Industry output in Ireland is substantially focused on high quality, low volume niche markets, such as organic or eco-certified products.

Much of Ireland's aquaculture is less intensive than in other nations. The salmon growing sites on the west coast of Ireland also occur in comparatively high energy environments, such that impacts like seabed anoxia and nutrient enrichment, are not as big an issue in Ireland when compared with other jurisdictions.

Sustainability is further supported by a number of successful national schemes such as CLAMS and ECOPACT. Such voluntary programmes focus on best practise, however, and do not necessarily require environmental benefits to be assessed or enforced.

Aquaculture can influence biodiversity and ecosystem functioning and services in a number of ways. The influences considered most important in Ireland are interactions with wild fisheries resources, physical damage to or replacement of habitat, organic and nutrient enrichment, as a vector for invasive species and through interactions with seals and birds. Each of these potential interactions are outlined in the review and approaches to mitigation are recommended.

The relative importance of these interactions varies depending on the environmental, economic, social , political and legislative context.

A key issue, which remains to be resolved, is the extent to which aquaculture operations are compatible with maintaining favourable conservation status in Natura 2000 sites.

The understanding of impacts of aquaculture in Ireland could be improved by development of a coordinated monitoring programme and research to understand (a) changes to communities and ecosystem processes in the water colum (which have been less well studied than those on the sea bed); (b) the extent of influence of individual aquaculture installations and how their influence combines and interacts with other local and global pressures; (c) the resistance and resilience of coastal ecosystems and the carrying capacity of Irish embayments and (d) how ecological changes induced by aquaculture translate into changes in provision of ecosystem services.

1. Aquaculture in Ireland

Since the 1980s, the global production of capture fisheries has stopped growing, while demand for fish has continued to increase rapidly. In response, world aquaculture production has increased by an average of 7% per annum and now produces half of the fish and shellfish consumed by humans (FAO, 2007 and 2009). The Irish aquaculture industry began in the 1970's. In 2007, the total production of shellfish and finfish in Ireland was 48,350 tonnes - 37,112 tonnes of shellfish (mainly oysters and mussels) and 11,238 tonnes of finfish (mainly salmon). The value of the sector was €150.7 million and it employs 2000 people (see Appendix). The economic and social value of aquaculture is heightened by the fact that it is one of the few industries with a strong presence in Ireland's remote coastal communities. While the production of shellfish is increasing steadily, salmon production has shown a decrease from 23,312 tonnes in 2001 to 9,923 tonnes in 2008. Industry output in Ireland is focused on high quality, low volume niche markets. An increasing proportion (almost 50% in 2003) of Irish salmon is produced to organic or eco-standards and sells at a premium (Browne et al. 2008). 90% of Irish salmon production in 2008 was independently accredited to either Organic or Eco-Standards and this pattern will continue into the future. The salmon growing sites on the west coast of Ireland occur in naturally higher energy, more exposed environments than the sea-lochs utilised by Scottish and Norwegian operators. Consequently, typical impacts associated with salmon farming, such as seabed anoxia and nutrient enrichment, are not as big an issue in Ireland when compared with other jurisdictions.

To ensure the sustainability of this industry, it is essential to better understand the interactions between aquaculture, biodiversity, ecosystem services and society. Biodiversity encompasses variation in genes, organisms and habitats. Changes to biodiversity, for example in terms of the numbers and identities of species present in an area, can affect the functioning of ecosystems, altering rates of production, nutrient cycling, etc., which in turn can influence the benefits to society that ecosystems provide. In this document, we briefly highlight some of the ways in which aquaculture can interact with biodiversity, emphasise possible consequences for society and suggest key areas for future research and policy development.

2. Influences of aquaculture on biodiversity and ecosystem services

The influences of aquaculture on biodiversity and ecosystem services are extremely varied and differ greatly depending on the species cultured, the culture methods and the environmental context. In general, the forms of aquaculture practiced in Ireland, and in the EU, are technically complex, draw on scientific input and, for the most part, are governed by a detailed regulatory framework. It should also be noted that aquaculture in Ireland is generally less intensive than in many other countries, so that issues that have been highlighted elsewhere may not apply here to the same extent. Below we list the activities and influences considered most likely to be important in an Irish context.

The importance of any particular issue depends on a number of factors, including legislation, society and economy. A key issue is the operation of the industry in Natura 2000 sites (Special Areas of Conservation and Special Protection Areas). As the specific conservation objectives relating to the features of these sites are developed, it will be necessary to establish baseline conditions, investigate how aquaculture affectsconservation status and take account of these issues in licensing future activities. This will require consultation among agencies and stakeholders. The other key EU directives are the Water Framework Directive and the new

Marine Strategy Framework Directive. A new EU strategy for aquaculture was published in April 2009. One of its three key elements was to ensure aquaculture remains sustainable by maintaining environmentally-friendly production methods. Strategic Environmental Assessments of aquaculture are being undertaken by the Loughs Agency (narrow geographic focus) and Bord Iascaigh Mhara (BIM) for its national operational programme for seafood development. BIM has also developed programmes in support of environmental management systems in aquaculture. These are ECOPACT – a simple Environmental Management System (EMS) that can be adopted by all farmers to improve environmental performance of their operations and at a higher level, the world's first independently accredited Eco-standards for Aquaculture (Salmon and Rope grown Mussels) (ISO65/ EN45011). Since the adoption of Commission Regulation 710/2009 laying down rules on the organic production of aquaculture animals and seaweed, organic production and certification has been embraced among Irish growers. Much of Irish salmon production is now organic and it is expected that by the end of 2011 up to 50% of mussel production may also be organic. BIM also support sustainable development of the sector and coastal zone management at bay scale through the CLAMS (Co-ordinated Local Aquaculture Management Systems) initiative. All of these schemes have been supported by industry (www.bim.ie). Conservation of biodiversity in Ireland is guided by the National Biodiversity Plan (www.epa.ie).

A goal of implementing EMSs and best management practices (BMPs) is either the improvement of environmental conditions or to minimise negative effects caused by the aquaculture activity. However, such schemes are in effect design standards. It is important to note that they typically include no means of measuring or validating environmental condition and therefore offer no absolute guarantee of environmental benefit (Clay 2008). Performance standards, on the other hand, measure specific environmental objectives, i.e. the effect on the activity on some aspect of the environment (e.g. free sulphide concentration in sediments). However, performance standards have resource implications in terms of monitoring and enforcement; they are likely more expensive to administer and implement that BMPs. There are no performance standards applied to shellfish aquaculture in Ireland, although, finfish aquaculture does have a range of protocols applied in order to measure compliance with certain environmental standards (Department of Agriculture, Food and the Marine, 2011).

2.1. Interactions with wild-fisheries resources

2.1.1 Capture of seed mussels. Aquaculture depends on harvesting wild resources which may have ecological impacts (FAO 2009, Davenport et al. 2003). In Ireland, mussel aquaculture depends on collection of seed through natural settlement of larvae directly on to ropes, from subtidal beds and to a lesser extent, intertidal areas, i.e.rock seed collection.

Potential interactions:

- Removal of juveniles from wild population. However, aquaculture introduces a larger population to the area and therefore a larger broodstock which mitigates these influences (assuming the seed is collected from the same waterbody as the culture activity). Some mussel seed settlements in the wild are ephemeral and may not survive predation and winter storms if not collected.
- Competition with predators (e.g. common scoter in subtidal mussel seed collection areas).
- Unintentional collection of non-target species (by-catch).
- Destruction of habitat (dredging, rock scraping).

Mitigation:

- In a growing number of countries seed are now produced in hatcheries (closed-cycle). However, as yet there are no commercial mussel hatcheries in Ireland.
- Appropriate assessment of the potential impact of dredge seed collection on the environment and conditions applying to duration, extent and timing of dredging applied to licences and quantity extracted.

2.1.2 Fish capture for feed production. As aquaculture production of predatory fish and crustacea increases, so does the capture of small fish (anchovies, sandeels, capelin, sprats, and herring) for feed production (Davenport et al. 2003). This is very much a global issue. Most fish meal and oil is derived from species such as anchovy, herring, sprat and blue whiting. These are short lived, fast growing stocks which are not favoured for direct consumption. The majority of these fisheries occur off south America and in Asia. These regions in turn are the largest fishmeal and oil producers. While global aquaculture production has continued to grow, use of fishmeal and oil by the sector has remained steady. This is because volumes of whole fish being used in the production of fish meal and fish oil are decreasing and volumes of fish by-products are increasing. It is also a result of substitution with vegetable ingredients such as soya meal and rapeseed oil (Wijkstrom, 2009). The International Fishmeal and Fish Oil Organisation (IFFO) have recently produced an independently accredited Responsibly Supply Standard and this has been widely adopted, already covering 20% of global supply (www.iffo.net).

The organic production strategy followed by most Irish producers is an important factor to consider. In organic production of finfish, the Marine Protein Index is much lower (<10 and as low as 3) than in conventional aquaculture which is as high as 45 in some production countries (C. McManus, pers. comm.).

Potential interactions:

- Food competition: adverse effects on wild predatory fish, marine mammals and seabirds.

Mitigation:

- Ongoing improvements on feeding efficiency through monitoring of FCR (Food Conversion Ratio) should be improved: reduce quantity of food, and at the same time reduce waste effects on the benthic-pelagic ecosystems. General improvements in feed quality though analysis and targeting of dietary requirements and substitution of a proportion for the feed with non fishmeal alternatives. Alternative food: fish captured from sustainable fisheries, substitute fish protein by soya protein, fish by vegetable oil. Substitution of protein and oil in fin fish feeds will be limited by the need for essential amino and fatty acids supplied in animal protein and oils. Thus substitution will not be total.

Populations derived from aquaculture, either due to spawning or escapes, can become established in the wild, sometimes with negative consequences for wild fisheries resources. This issue is addressed below in Section 2.4.

2.2. Physical changes to the habitat

Structures are used in most aquaculture: fish cages, oyster trestles, mussel lines etc.

Potential interactions:

- Modify water circulation.
- Antifouling used to prevent colonisation of fish nets is toxic for non-target species. However, anti-fouling is not commonly used in fin-fish farming in Ireland. Normal practice in Ireland is to use high pressure washing with seawater followed by natural drying on the seashore. Anti fouling is never used on oyster and mussel structures.
- Provide substrata for invasive species.
- Increase habitat complexity, provide hard substrata.
- Act as artificial reefs: may promote secondary production and biodiversity.
- Provide food and shelter to wild fish and invertebrates.
- Fouling organisms could act as natural biofilters and remove the dissolved and particulate waste coming from fish farm.

Mitigation:

- Careful use of chemicals. Minimise chemical usage.
- Careful site management and maintenance – net washing etc.
- Carrying capacity studies to assess critical mass of structures for causing above effects.

2.3. Organic and nutrient enrichment

The environmental impacts of finfish farming are mainly related to the accumulation of organic compounds (organic nitrogen, phosphorus and carbon from faecal pellets and uneaten food) under fish cages, and the excretion of inorganic compounds into the water column, mainly total ammonia nitrate (NH_3 and NH_4^+), urea and phosphate (Hargrave 2005). Shellfish produce less waste than finfish farms as feed is not added into the environment, however suspension-feeding bivalves produce biodeposits which accumulate on the sea bed (Black et al., 2001; Cranford et al., 2006).

Potential interactions:

- Eutrophication: increased oxygen demand by bacteria to degrade organic matter, potentially leading to hypoxia and anoxia.
- Nitrate reduction induces ammonium (NH_4^+) release and sulphate reduction induces sulphide accumulation with direct toxic effects on benthic organisms.
- Shift from a functionally diverse benthic community to a low diversity community dominated by opportunistic species such as deposit-feeders (or only bacteria in extreme cases).
- Negative effects on seagrasses (protected and highly productive ecosystems).
- Increased nutrient concentration and alteration of nutrient ratios in water column may induce changes in planktonic community. e.g. increased N:P ratio may promote dinoflagellates and Harmful Algal Blooms (with negative impacts on aquaculture production).

Mitigation:

- Improve feeding efficiency and reduce waste.
- Fallowing, rotation of cages, reduction of culture densities.
- Bioremediation (using deposit-feeders), polyculture (Integrated Multi-Trophic Aquaculture).
- It should be noted that terrestrial agriculture is generally a far greater contributor to nutrient loads in Irish coastal waters than aquaculture (possible exceptions include Killary Harbour and Mulroy Bay).

2.4. Invasive species

Aquaculture can become accidentally or intentionally a vector promoting the spreading of species outside their natural range (Carlton 1996, Wolff and Reise 2002), some of which become invasive and damage native ecosystems. This has been ameliorated by recent enforcement of regulations and the "ICES Code of Practice on the Introductions and Transfers of Marine Organisms" (ICES 2005, ICES 2006). Aquaculture can also become the victim of invasive species introduced by other vectors e.g. sailing and commercial shipping. Currently, the greater issue of concern is some cultured species themselves becoming invasive.

Ireland is a contracting party to a number of international conventions and agreements which require them to take account of invasive introduced species. The Convention on Biological Diversity (CBD) aims to prevent introductions, control invasive species and develop legislation. European Directives (e.g. Natura 2000 within the EU Habitats Directive, EU Water Framework Directive) and national legislation (e.g. Wildlife (Amendment) Act 2000, National Biodiversity

Plan) are other legislative drivers. Ireland is also committed to the EU target of halting the loss of biodiversity by 2010.

Some examples of invasive species in Ireland for which aquaculture was the likely vector:

- Wireweed (*Sargassum muticum*): large brown alga from Japan and Korea, can grow up to 16 m in length, forming floating mats on the sea surface, occupy hard substrates on sheltered shores where it can form dense monospecific stands, can reduce the available light for understory species, dampen water flow, increase sedimentation rates and reduce ambient nutrient concentrations available for native species.
- Pacific Oyster (*Crassostrea gigas*) (deliberately introduced aquaculture species): filter-feeding bivalve, one of the main species used for aquaculture purposes worldwide. In many countries, it has already become an invasive species. Once it becomes established it can form large and dense reefs affecting and changing habitat structure and native communities. Its status in Ireland is not clear yet. It often functions as a vector for other non-native species.

A more detailed list of alien aquatic species in Ireland and their current status and impacts is given by Minchin (2007).

Potential interactions:

- Genetic level: Hybridisation, alteration of genetic diversity, out-breeding depression, reducing disease and parasite resistance, selection pressure on native populations (Nell 2002, Pifferer et al. 2009)
- Species level: Competition for food, predation on native species, introduction of hitch-hiking non-native species, carrying of parasites and pathogens exerting impacts on native species (Ruesink et al. 2005, Reise et al. 2006, Van der Velde et al. 2006)
- Community level: Modification and change of trophic structure and communities, change in macrobenthic community composition, large populations of invasive filter feeders can reduce food availability to species dependent on suspended particulate food, alteration of food webs (Reise et al. 2006, Ruesink et al. 2005)
- Habitat level: Alteration of physical structure, change of bottom topography, carrying capacity, accumulation of pseudofaeces and fine sediment through filtration activity, changes in sediment and near-bottom currents, reduce/increase in biodiversity (Streftaris et al. 2005)
- Economy: High cleaning costs of high infection rates on mollusc aquaculture structures, reduced harvesting quantities or qualities, technical constructions affected (Van der Velde et al. 2006)

Mitigation:

Proposed by “ICES Code of Practice on the Introductions and Transfers of Marine Organisms” and by the Invasive Species Ireland project to reduce the risk of invasion.

- Use sterile triploids in aquaculture (not currently permitted in organic finfish production).
- Avoid spat from areas where infestations with unwanted species occur.
- Use quarantine facilities, disinfection.
- Use native species for aquaculture.
- Source juveniles only from approved and accredited hatchery facilities.
- Risk assessments and regular monitoring.
- Active control and eradication where species have become established outside licensed culture areas.

2.5 Interactions with seals and birds

Aquaculture may have both positive and negative impacts on seals and birds which can be influential in terms of public opinion and in relation to compatibility with conservation objectives.

Potential interactions:

- Seal populations benefit from theft of salmon from cages; salmon farmers have retaliated at times.
- Birds are thought in some cases to benefit from the habitats and food provided by aquaculture installations and in others to suffer through reduced resources (e.g. the Wadden Sea).

Mitigation:

- Increase awareness among farmers of the protected status of species.
- Farmers can participate in census and other studies to improve understanding of protected species behaviour and status.

2.6 Ecosystem functioning

The effects described above (removal of wild resources, physical changes to habitats, organic and nutrient enrichment, invasive species) may all have consequences for ecosystem functioning, either directly in their own right or indirectly as a result of modifications to biodiversity and the physico-chemical aspects of ecosystem structure. In particular, the productivity and carrying capacity of embayments will be influenced by:

- Nutrient and organic enrichment
- Biogeochemical processes in the sediment, particularly nutrient cycling, which is affected by processes involving filter-feeding, excretion, remineralisation of nutrients from particulate organic matter, loss of nutrients through harvesting and changes to sediment structure caused by dredging.
- Loss of habitats, e.g. seagrass beds and hard substrata affected by dredging.

The nature and magnitude of effects will vary depending on the timing and intensity of aquaculture, the filtering rate of the cultured organism and on the flushing characteristics of the environment (the natural hydrodynamics of the environment), which themselves can be affected by aquaculture structures, with potential effects on physical processes such as erosion and accretion of sediment and ecological processes such as larval dispersal and recruitment.

3. Current position of our understanding

Many of the issues described above have been researched extensively at the international level, but few have been targeted for research within Ireland. A valuable data-set is being accumulated through a comprehensive monitoring programme for shellfish and finfish aquaculture which meets European demands (Browne et al. 2008). However, the goal of these monitoring programmes is to ensure consumer safety, not to inform on status of the environment where the culture activity takes place. As it currently stands, there are no monitoring programmes in any EU member state (including Ireland) that assess the impact of shellfish on system ecology. The Aquaculture Stewardship Council, in association with the WWF, has developed a set of standards to ensure shellfish aquaculture is conducted in an environmentally and socially sustainable fashion (World Wildlife Fund, 2010). It is unclear, at this time, as to the status of this voluntary certification scheme.

3.1 Shellfish monitoring currently in place

- Shellfish biotoxin and phytoplankton monitoring. Sample of shellfish and water from shellfish and finfish aquaculture sites are routinely collected and analysed by the Marine Institute. Results of analysis are reported within three days (93.4%).

- Bacteriological contamination
- Virological contamination
- Contaminants in shellfish and shellfish waters
- Shellfish health status

3.2 Finfish monitoring currently in place

- Sea lice
- Benthic monitoring
- Residues monitoring in finfish
- Finfish health status

A lot of individual farm scale and bay scale monitoring and observations exist. It would be useful to compile the information into a usable format and to develop a more coordinated overall monitoring programme.

4. Ecosystem services: biological, social and economic perspectives

Ecosystem services from marine ecosystems include climate regulation, erosion control, pollution control, provision of food and other biological resources (e.g. alginates, pharmaceuticals), aesthetic value and inspiration, underpinning recreation and tourism and a range of cultural and social traditions (Millenium Ecosystem Assessment 2005). In Ireland, marine environments underpin aquaculture, fisheries and recreational and tourist industries that are vital to the society and the economy, particularly of remote coastal communities. In addition to direct employment in these industries, a large number of jobs are maintained in supporting industries, such as the supply of equipment, fuel, etc. The valuation of these services in monetary terms is a developing science. A recent national estimate of the value of biodiversity to Ireland's economy yielded an overall value of €2.6 billion per annum, but took a very narrow view of marine systems, focussing only direct valuation of fisheries and aquaculture (Government of Ireland 2008).

Aquaculture brings a substantial positive benefit to society and the rural economy of Ireland (see Introduction). Aquaculture also depends on ecosystems, for the provision of fish food, for the natural control of parasites and for the assimilation of waste from farms (Government of Ireland 2008). Its management therefore requires a carefully balanced approach. When society has multiple goals, many of which depend on biodiversity, ecosystem services, and the many constituents of well-being, difficult decisions involving trade-offs among competing goals have to be made. When assessing the interactions between aquaculture and biodiversity it is essential to take into account the "positive" and "negative" influences of aquaculture, and follow an ecosystems approach. In assessing the trade-off between costs and benefits of aquaculture, it is useful to consider the production, ecological and social carrying capacity of different localities (McKindsey et al. 2006 have reviewed the concept of carrying capacity).

Appropriate management requires an integrated approach taking into account factors including nutrient input from land, etc, It is important to work in collaboration with aquaculturists and other stakeholders. In Ireland, the Minister and the Department of the Marine and Natural Resources (Now Department of Agriculture, Food and the Marine) have adopted the policy of CLAMS: Co-ordinated Local Aquaculture Management Systems. The concept is to amass all relevant baseline data and to formulate an aquaculture development plan for the bay while incorporating and extending the successful concepts of Single Bay Management to all farmed species (http://www.bim.ie/templates/reports). CLAMS is very much a living process addressing issues that arise on an ongoing basis and taking proactive measures to improve the management of aquaculture at a local level.

5. Issues that need further exploration and/or research

Localised impacts of aquaculture on benthic communities have been comparatively well documented. Changes to pelagic communities are less clear. It is also unclear how any induced changes will translate into changes in ecosystem functioning and provision of goods and services. This requires a combined approach involving ecologists, socio-economists and stakeholders.

The limits to the spatial extent of impacts of aquaculture and their duration need to be characterised. It is essential that we expand our understanding of impacts at larger scales in space and time. These may be driven by the propagation of localised impacts of individual installations, the accumulation of localised impacts of aquaculture and/or the combined effects of aquaculture with other activities. Such activities range from recreational use of the coastal zone to sewage outfalls and construction activities. Larger scale drivers, such as the forecast global changes in sea temperature, storminess, precipitation and sea level may also influence impacts of aquaculture and its interactions with other activities.

Further research is also needed to improve our understanding of the resistance and resilience of different ecosystems to perturbation and the carrying capacity of Irish embayments. Mitigation and remediation strategies need to be based on this knowledge and require additional research to assess their effectiveness.

Targeted research may also be needed to assess the compatibility of aquaculture activities with the conservation objectives of Special Areas of Conservation and Special Protection Areas to inform the development of management plans for those areas.

All of these issues could be addressed with a carefully designed and coordinated long term monitoring programme combined with targetted experimental investigations. Modelling approaches are also required to collate existing knowledge and information, allowing prediction of future changes and management decision support.

6. Key documents for additional information

- Status of Irish Aquaculture 2007 (Browne et al. 2008)
- Davenport, J., Black, K., Burnell, G., Cross, T., Culloty, S., Ekaratne, S., Furness, B., Mulcahy, M. and Thetmeyer, H. (2003) Aquaculture: the ecological issues. Blackwell Scientific, Oxford.
- Life-Cycle Assessment of Salmon Fisheries and Aquaculture (www.ecotrust.org/lca)
- The Invasive Species Ireland project (http://www.invasivespeciesireland.com/) developed a Marine Aquaculture Code of Practice.
- FAO (2009) The state of world fisheries and aquaculture 2008. Fisheries and Aquaculture Department. Food and Agriculture organization of the United Nations, Rome.
- Government of Ireland (2008) The Economic and Social Aspects of Biodiversity: Benefits and Costs of Biodiversity in Ireland. The Stationery Office, Government Publications, Ireland (download from www.environ.ie).
- National Research Council (2010) Ecosystems concepts for sustainable bivalve culture. Academic, Washington, DC.

References cited

Black K.D. (2001) Environmental impacts of aquaculture, Black KD (ed) Sheffield Academic Press, Sheffield

Browne R., Deegan B., Watson L., Mac Giolla Bhríde D., Norman M., Ó'Cinnéide M., Jackson D. and O'Carroll T. (2008). Status of Irish Aquaculture 2007. Marine Institute, Bord Iascaigh Mhara and Údarás na Gaeltachta. 142 pp.

Carlton J. (1996) Marine bioinvasions: the alteration of by nonindigenous species. Oceanography 9: 233-247.

Clay JW (2008) The role of better management practices in environmental management. In: Tucker CS, Hargreaves JA (eds) Environmental best management practices for aquaculture. Wiley, Hoboken

Cranford P., Anderson R., Archambault P., Balch T., Bates S., Bugden G., Callier M.D., Carver C., Comeau L., Hargrave B., Harrison G., Horne E., Kepay P.E., Li W.K.W., 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.

Davenport J., Black K., Burnell G., Cross T., Culloty S., Ekaratne S., Furness B., Mulcahy M. and Thetmeyer H. (2003) Aquaculture: the ecological issues. Blackwell Scientific, Oxford.

Department of Agriculture, Food and the Marine. 2011. Monitoring Protocols 1-5 for Offshore Finfish Farms. www.agriculture.gov.ie/fisheries/aquacultureforeshoremanagement/monitoringprotocols/ Date of access: December 2011

FAO (2007) www.fao.org/statistics/

FAO (2009) The state of world fisheries and aquaculture 2008. Fisheries and Aquaculture Department. Food and Agriculture organization of the United Nations, Rome.

Government of Ireland (2008) The Economic and Social Aspects of Biodiversity: Benefits and Costs of Biodiversity in Ireland. The Stationery Office, Government Publications, Ireland (download from www.environ.ie).

Hargrave BT (ed) (2005) Environmental effects of marine finfish aquaculture: the handbook of environmental chemistry. Water pollution, part M, Springer-Verlag, Berlin, Vol 5, pg 468.

ICES (2005) ICES Code of Practice on the Introductions and Transfers of Marine Organisms 2005. Code de Conduite du CIEM pour les Introductions and Transferts d'Organismes Marins 2005. ICES, Copenhagen

ICES (2006) Report of the Working Group on Introductions and Transfers of Marine Organisms. ICES CM 2006/ACME:05. 334 pp.

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.

Minchin D. (2007) A checklist of alien and cryptogenic aquatic species in Ireland. Aquatic Invasions 2(4): 341-366.

Nell J.A. (2002) Farming triploid oysters. Aquaculture 210(1-4): 69-88.

Pifferer F., Beaumont A., Falguière J.C., Flajšhans M., Haffray P. and Colombo L. (2009) Polyploid fish and shellfish: Production, biology and applications to aquaculture for performance improvement and genetic containment. Aquaculture 293(3-4): 125-156.

Reise K., Olenin S. and Thieltges D. (2006) Are aliens threatening European aquatic coastal ecosystems? Helgoland Marine Research 60(2): 77-83.

Ruesink J., Lenihan H.S., Trimble A.C., Heiman K.W., Micheli F., Byers J.E. and Kay M.C. (2005) Introduction Of Non-Native Oysters: Ecosystem Effects and Restoration Implications. Annual Review of Ecology, Evolution, and Systematics 36: 643-689.

Streftaris N., Zenetos A. and Papathanassiou E. (2005) Globalisation in marine ecosystems: the story of non-indigenous marine species across European Seas. Oceanography and Marine Biology: An Annual Review 43: 419-453.

The Millennium Ecosystem Assessment (2005) http://www.millenniumassessment.org

Van der Velde G., Rajagopal S., Kuyper-Kollenaar M., Bij de Vaate A., Thieltges D.W., MacIsaac H.J. (2006) Biological invasions – concepts to understand and predict a global threat, In: Bobbink R., Beltman B., Verhoeven J.T.A., Whigham D.F. (eds.) Wetlands as natural resource. Volume 2. Wetlands: functioning, biodiversity, conservation and restoration. Ecological Studies, Springer Verlag, Berlin.

Wijkström, U.N. 2009. The use of wild fish as aquaculture feed and its effects on income and food for the poor and the undernourished. In M.R.Hasanand M. Halwart(eds). Fish as feed inputs for aquaculture: practicesPaper. No. 518. Rome, FAO. pp. 371–407.

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: Leppäkoski, E., Gollasch, S., Olenin, S. (Eds), Invasive aquatic species of Europe. Kluwer Academic Publ, Dordrecht, 193-205.

World Wildlife Fund (2010) Bivalve aquaculture dialogue standards, 50 pp. http://www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem17872.pdf Date of Access: December 2011

Appendix

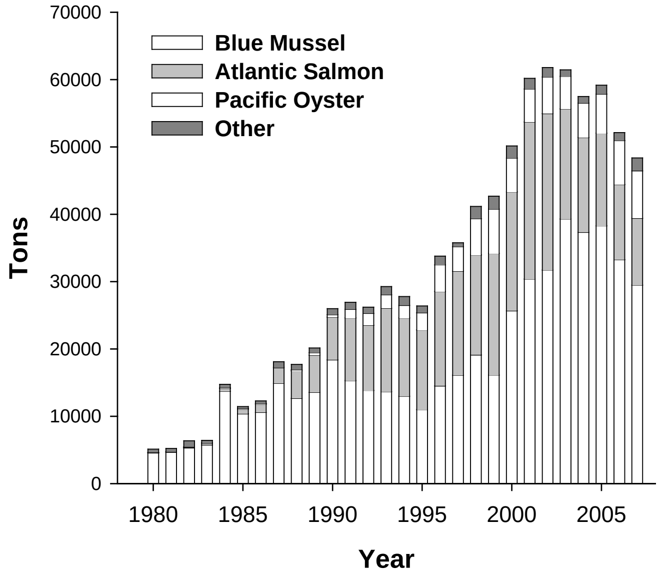

Figure 1. Irish aquaculture production (adapted from FAO 2007 and Browne et al. 2008 - Status of Irish Aquaculture 2007).

Table 1. Total aquaculture production (volume and value) in Ireland in 2007. Adapted from Browne et al. 2008- Status of Irish Aquaculture 2007. Although the current review focuses on marine aquaculture, freshwater species have been left in this table for completeness.

Species	Tonnes	%		Value (million)	%
Rope mussel	11200	30.2		7.8	16.5
Bottom mussel	18270	49.2		20.9	44.2
Pacific oyster	7032	18.9		15.4	32.5
Native oyster	382	1.0		1.6	3.4
Clam	170	0.5		1.0	2.2
Scallop	58	0.2		0.3	0.7
Other (abalone, urchin, lobster)				0.2	0.4
Total shellfish	**37112**			**47.3**	
Salmon ova/smolt				2.9	4.9
Salmon	9923	88.3		51.3	87.8
Sea reared Trout	507	4.5		1.9	3.3
Freshwater Trout	760	6.8		2.0	3.5
Other (cod, perch, Arctic charr, ornamental fish)	48	0.4		0.3	0.5
Total finfish	**11238**			**58.4**	
Total aquaculture	**48350**			**105.7**	