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Corrigendum

Section **1.2 Pharmaceuticals and pesticides, Anti-parasitics** originally detailed an incorrect reference to a study on the lethality of anti-parasitic drug cypermethrin to lobsters, and has been updated with more recent information on pesticide toxicity in November 2015.

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Introduction

Is sustainable aquaculture possible?

Aquaculture is facing a new era of expansion in Europe. What are the environmental implications of this, and how can the sector expand sustainably? This Future Brief from Science for Environment Policy presents an overview of research into aquaculture's impacts, and considers how it could develop in harmony with environmental goals.

Fish farm at Bussi, in Abruzzo, Italy. ©iStock.com/seraficus

The EU's Blue Growth Strategy[1] identifies aquaculture — the farming of fish, shellfish and aquatic plants — as a sector which could boost economic growth across Europe and bring social benefits through new jobs. The reformed Common Fisheries Policy[2] also aims to promote the sector and EU Member States are currently developing national aquaculture strategies.

Presently, a quarter of seafood products consumed in the EU (including imports) are produced on farms; in 2011, 1.24 million tonnes of aquaculture goods were produced in the EU, worth €3.51 billion (European Commission, 2014a). There are over 14 000 aquaculture enterprises in the EU, directly employing 85 000 people in total (European Commission, 2014b). In contrast with other regions of the world, aquaculture production is stagnating in the EU, while imports are rising.

At the same time, there is a growing gap between the amount of seafood consumed in the EU, and the amount caught from wild fisheries. The European Commission calls for this gap to be partly filled with environmentally responsible aquaculture (European Commission, 2013). Aquaculture thus has an important role to play in Europe's food security as well as its economic growth.

1. http://ec.europa.eu/maritimeaffairs/policy/blue_growth/
2. http://ec.europa.eu/fisheries/cfp/index_en.htm

In its expansion, aquaculture must continue to respect environmental legislation. This report outlines research into a selection of water and ecological impacts of aquaculture, alongside information on existing and forthcoming measures to mitigate negative impacts. It also highlights the possibility that filling certain knowledge gaps could help to further improve aquaculture's sustainability.

In some cases, aquaculture may have positive effects on nature and water quality, and it has been suggested that certain types of farming could help meet the goals of environmental legislation. The importance for the industry of water quality in the wider environment is also considered.

Aquaculture is a hugely diverse industry (see Box 1), and it should be emphasised that environmental impacts cannot be generalised across the sector. Impacts vary with species, farming methods and management techniques, precise location and local environmental conditions and wildlife.

Aquaculture and EU policy

Aquaculture's environmental impacts are regulated under a range of EU legal requirements that address broader issues including water quality, biodiversity protection and sustainable development and planning. Both its impacts and regulations are often interrelated. For instance, water pollution from aquaculture operations may affect biodiversity.

Research presented in this report is relevant to current EU legal requirements affecting aquaculture. These include the following.

- The **Marine Strategy Framework Directive (MSFD)**[3] requires EU Member States to achieve 'Good Environmental Status' for their marine waters by 2020, as judged against a range of 11 so-called 'descriptors'[4]. Thus, national aquaculture strategies must ensure that aquaculture does not have negative impacts in terms of non-indigenous species, eutrophication, seafloor integrity, concentrations of contaminants (both in the water generally and in seafood specifically), populations of commercial fish or marine litter.

- **The Water Framework Directive (WFD)**[5] addresses pollution and biodiversity concerns in inland, coastal and transitional waters (e.g. estuaries and fjords). It requires Member States to attain 'good ecological status' and 'good chemical status' in these waters. Pollution by 'priority' chemical substances, some of which are used in aquaculture, must be progressively reduced and, in some cases, phased out completely.

- Aquaculture operations must respect wildlife protection requirements under the **Birds** and **Habitats Directives**[6]. In particular, they must comply with the conservation objectives of sites included in **Natura 2000**[7], the EU network of protected areas, and be subject to an Appropriate Assessment prior to authorisation in line with Article 6 of the Habitats Directive[8].

- The **Regulation on the use of alien and locally absent species in aquaculture**[9] addresses the movement of alien species for aquaculture purposes. Operators must conduct prior risk assessments and obtain permits to transfer alien aquatic species. The newly adopted **EU Regulation on the prevention and management of the introduction and spread of invasive alien species**[10] will also apply to aquaculture. It will address threats posed by invasive alien species through actions which: (1.) restrict the introduction and spread of invasive alien species; (2.) establish effective early warning and rapid reaction mechanisms; and (3.) manage invasive alien species that are already present and widespread in the EU. It will be compatible with the Regulation on the use of alien and locally absent species in aquaculture.

- Planning and development of new aquaculture sites fall under the **Environmental Impact Assessment (EIA)**[11] and **Strategic Environmental Assessment (SEA)**[12] directives. These allow environmental concerns to be taken into account very early on in planning processes, thus avoiding or minimising negative impacts. In addition, the recently-agreed **Directive on Maritime Spatial Planning (MSP)**[13] aims to promote sustainable development and use of marine resources, including for aquaculture, through Maritime Spatial Plans to be established in each Member State by 2021.

3. http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm
4. The descriptors are laid out in full in Annex 1 of the MSFD.
5. http://ec.europa.eu/environment/water/water-framework/index_en.html
6. http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm
7. http://ec.europa.eu/environment/nature/natura2000/index_en.htm
8. See Commission Guidance on Aquaculture and Natura 2000 at: http://ec.europa.eu/environment/nature/natura2000/management/docs/Aqua-N2000%20guide.pdf
9. http://europa.eu/legislation_summaries/environment/nature_and_biodiversity/l28179_en.htm
10. http://ec.europa.eu/environment/nature/invasivealien/index_en.htm
11. http://ec.europa.eu/environment/eia/eia-legalcontext.htm
12. http://ec.europa.eu/environment/eia/sea-legalcontext.htm
13. http://ec.europa.eu/maritimeaffairs/policy/maritime_spatial_planning/index_en.htm

BOX 1.

Classifying aquaculture

Aquaculture is very diverse, but operations can be broadly grouped by the following characteristics:

By water type
This is mainly a distinction between **marine** and **freshwater** aquaculture. Marine aquaculture can also take place in brackish waters, where sea and freshwaters mix, as well as on land (e.g. in tanks).

By species type
Species can be classified as '**finfish**' (such as salmon or carp), **shellfish** (which includes bivalves, such as mussels, and crustaceans, such as prawns) or **plants** (such as seaweed or watercress).

By intensity
In **intensive** aquaculture, managers supply the cultured species with all their feed. No feed is provided in **extensive** aquaculture as feed comes from the natural environment. In a **semi-intensive** system, managers supplement natural sources of feed.

By water flow
In a **closed system**, such as a tank or enclosed pond, water is contained and may be tightly controlled and recirculated. In an **open system**, such as a sea cage or shellfish raft, water from the natural environment flows freely through the farm. In a **semi-closed system**, some water is exchanged between an enclosed site and the natural environment.

EU aquaculture per product type
(percentage of total volume, EU–27, 2011)

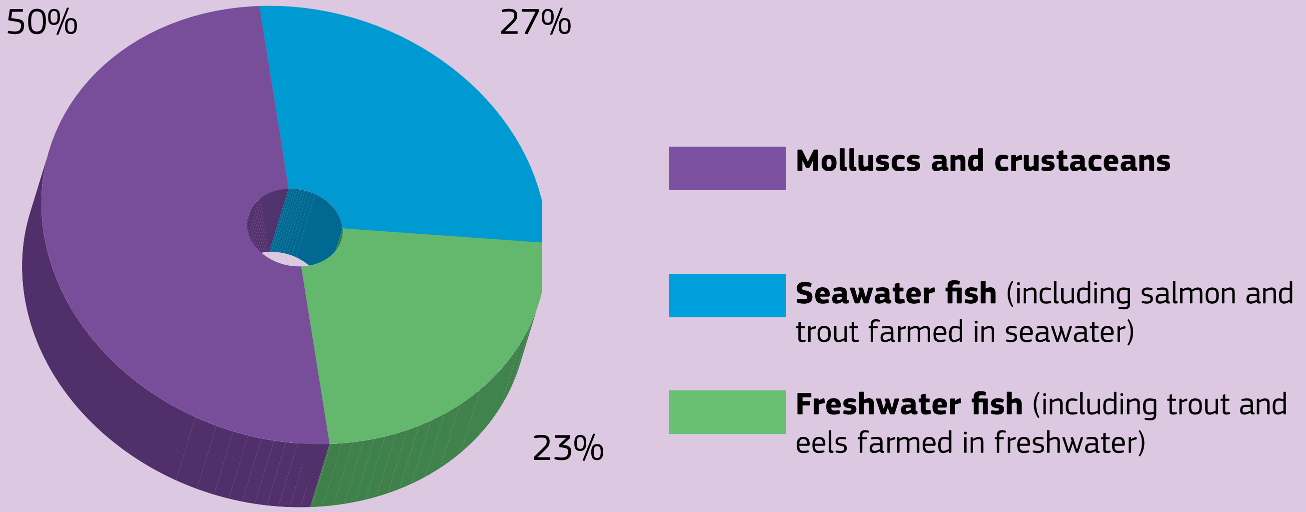

Figure 1: Source data: eurostat and EUMOFA. Reproduced from European Commission (2014c).

1. Pollution and aquaculture

This chapter considers how outgoing water quality from aquaculture farms can be managed (sections 1.1–1.3). It also discusses how environmental legislation can help ensure the clean water that is essential to aquaculture (section 1.4).

1.1 Organic waste and nutrient pollution

Concerns have been raised about organic waste and nutrients released by fish farms, especially open farms from which waste and water flows freely. Waste is released as solid particles (e.g. fish faeces and uneaten feed), while dissolved nutrients (nitrogen and phosphorus) are released by fish (through their gills and in their urine), as well as by the solid waste when it breaks down.

These can negatively affect benthic (seafloor) ecosystems in the local vicinity of the farm, causing ecological impacts. For example, Sanz-Lázaro *et al.* (2011) found that effluent from a Spanish sea bass and sea bream farm disturbed maërl beds (a sensitive red algae habitat protected under the Habitats Directive). Recently, changes in sediment chemistry and benthic biodiversity have been recorded beneath a deep-water (190 metres) intensive salmon farm in Norway (Valdemarsen *et al.*, 2012; Bannister *et al.*, 2014).

Nutrients released from fish farms have the potential to cause eutrophication. There is evidence that levels of nutrients may be elevated up to a distance of about 100 metres around a farm, but there is, as yet, limited evidence of regional impacts. However, Price & Morris (2013) highlight a gap in scientific knowledge of how nutrients spread over large areas, and of the effects of ever-increasing production from multiple farms in a region.

One study which does point to regional impacts was conducted by Sarà *et al.* (2011). This found that chlorophyll-a concentrations (an indicator of eutrophication monitored under the WFD) were three to ten times higher in the Gulf of Castellammare (size: 370 km^2), Italy, than in open waters. It linked this to sea bream, sea bass and bluefin tuna farming in the Gulf, where water currents are unable to disperse pollution easily.

Managing nutrients and organic waste

Concerns have been voiced about farms in waters which are already nutrient-rich, such as the Baltic Sea (e.g. by Saikku & Asmala, 2010; Coalition Clean Baltic, 2014). Langan (2004) recommends that only 'extractive species' (which absorb nutrients), such as bivalves or seaweed, be farmed in such waters.

Such species also have the potential to remove nutrients emitted by other industries. Shellfish farming itself has been proposed as an ecosystem service tool for lowering nutrients in water from all sources, to help meet the WFD's objectives. For example Petersen *et al.* (2014) estimated that harvesting 50–60 tonnes of mussels per hectare in a eutrophic Danish fjord per year would extract 0.6–0.9 tonnes of nitrogen and 0.03–0.05 tonnes of phosphorus per hectare.

Locating aquaculture operations appropriately is very important and strategic planning can avoid or minimise most of aquaculture's environmental impacts. Better siting is one reason for the drop in the negative impacts of nutrient pollution observed over the past 20 years: computer models allow operators to assess a site's 'assimilative capacity' for aquaculture effluent and pick the most suitable locations for farming. This can be determined as part of the Environmental Assessments needed to obtain a licence to operate and as required under the EIA Directive or under the 'Appropriate Assessment' required for Natura 2000 sites[14]. 'Assimilative capacity' describes the ability of a specific site to accommodate a fish farm without its pollution causing negative environmental impacts, i.e. pollutants can be sufficiently diluted. It depends on local conditions, including water flow, water depth and the farm's size.

However, researchers have warned against relying on dilution to deal with nutrient pollution, particularly if aquaculture is to expand (Pittenger *et al.*, 2007; Troell *et al.*, 2009). Additional changes and measures are thus needed.

Several measures are feed-related. Ongoing improvements to fish feed's digestibility (so that fish absorb more, and release less nutrients) have lowered organic waste, as well as operating costs (Bureau & Hua, 2010). As with other forms of livestock, fish can be selectively bred to improve their 'feed-conversion ratio' (i.e. the kilograms of feed needed to produce one kilogram of product). To illustrate, Brennan

14. http://ec.europa.eu/environment/nature/natura2000/management/guidance_en.htm

(2002) calculated that lowering the feed-conversion ratio of intensively farmed Australian prawns from 2.5 to 1 could cut feed costs by AUS $25 000 (c. €17 000), and reduce nitrogen load by nearly 300 kilograms per hectare of farm, assuming that 10 tonnes of prawns are produced per hectare.

Scientists have also called for the use of locally sourced fishmeal for rainbow trout aquaculture in the Baltic Sea to recycle existing nutrients in the Sea, as opposed to adding to levels through imported fishmeal (Saikku & Asmala, 2010; Gyllenhammar, Håkanson & Lehtinen, 2008).

New forms of farming are being considered. For instance, it has been proposed that shellfish and seaweed could be farmed alongside — or nearby — finfish to mitigate nutrient pollution from finfish farming. This method, called integrated multi-trophic aquaculture, is attracting attention as a possible future route for sustainable aquaculture. See Box 2 for discussion.

BOX 2.

Integrated multi-trophic aquaculture: ecologically-engineered farming

Integrated multi-trophic aquaculture (IMTA) involves farming finfish alongside either algae or shellfish. The waste nutrients from the finfish are consumed by the algae and shellfish, thus partly mitigating the environmental impacts of finfish culture.

IMTA has been practiced for centuries in Asia, but has yet to become established in Europe. Scientific research into its impacts is in its early stages, but so far indicates that IMTA could bring financial benefits by boosting algae and shellfish growth.

A number of case studies have explored its ability to reduce nutrient pollution. Results vary considerably with the type of farm and location, but in general suggest that IMTA could help tackle the problem. Details of case studies and findings include:

- A full-scale IMTA farm is currently being piloted in Denmark by the KOMBI project, which is due for completion in May 2015 (www.kombiopdraet.dk — in Danish). The farm aims to be ‘zero impact’. The project team predict that harvesting 7000-9000 tonnes of mussels will recover 100% of nutrients (88 tonnes of nitrogen and 9.6 tonnes of phosphorus) released by 2105 tonnes of rainbow trout each year. The mussels are cultured within the same WFD water body as the trout, but are several miles away. They are farmed using a space-efficient ‘smartfarm’ system, i.e. on nets, rather than longlines (Carl, 2014a; 2014b).

- In a Portuguese experiment, 12 tanks (total cultivation area of 18 m^2) of the seaweed *Gracilaria vermiculophylla* (used to make agar) removed 0.5% of nitrogen from the effluent of a land-based, recirculating sea bass, turbot and sole farm (Abreu *et al.*, 2011). The removal rate could be increased if more seaweed was grown, but more land would be needed for the seaweed’s tanks (900 m^2 for 25% removal and 0.36 ha for 100% removal).

- Holdt & Edwards (2014) conclude that blue mussels are more effective than kelp in removing nutrients, and need much less space, based on experiences in Denmark and Ireland.

The EU IDREEM project is currently developing and testing IMTA systems, and will provide more information and tools for sustainable marine aquaculture in Europe: www.idreem.eu

1.2 Pharmaceuticals and pesticides

Aquaculture farms often provide conditions which allow disease to flourish more easily; for example, animals are often stocked at a higher density than wild fish. Most veterinary products and disinfectants to manage animal disease have been judged to have minimal negative environmental impacts if used correctly (IUCN, 2007). Many sectors of aquaculture, such as shellfish farming or most extensive pond farming, use no medicines, and pharmaceutical use is closely regulated and inspected in all EU Member States. However, problems, such as risks to non-target species, may occur where pharmaceuticals or disinfectants are used above safe limits as defined in relevant EU and national legislation. It is also possible, in view of uncertainties regarding potential effects, that the use of some products even within those limits might create problems for non-target species.

Antibiotics

Use of antibiotics has been flagged as a particular concern in open aquaculture where they enter the surrounding marine environment via fish faeces and can persist for long periods in sediment. In Europe, they are typically administered via medicated feed, but only a percentage is absorbed by the fish. For instance, Rigos *et al.* (2004) estimated that 60–73% of the antibiotic oxytetracycline administered to sea bass on Greek farms is released to the environment via the fishes' faeces.

Very little is actually known about the effects of antibiotic use on the surrounding marine environment (Pittenger, *et al.* 2007). However, studies conducted to date indicate it may carry ecological risks. For example, Ferreira *et al.* (2007) found that high concentrations of oxytetracycline and florfenicol, both active against *furunculosis* in salmon, inhibit growth of the wild alga *Tetraselmis chuii*, an important food source for other marine organisms. Such studies are largely limited to short-term laboratory studies and the concerns they raise highlight the need to further investigate the effects of 'real-world' chronic, low-level exposure to antibiotics on wild species.

In the past, antibiotics were used much more liberally in aquaculture. In response to growing awareness of possible ecological and human health risks and stricter regulations on their use, they are now generally used as a last resort. Improvements in farming practices have led to improved animal health and have reduced the need for antibiotics. Recognition of antibiotics' overuse, which can lead to drug resistance of fish diseases, as well as their cost has further incentivised improved farming practices as a solution to disease management. The development and use of vaccines is also a key factor in reducing the need for antibiotics.

A key issue of debate is whether the drug resistance from fish bacterial disease can be transferred to human bacterial disease — thus contributing to one of the world's most significant healthcare problems. It is clear that resistance-causing genes can flow between different species of bacteria. Aquaculture may thus have the potential to contribute to the widespread pool of resistant bacteria in the environment. Taylor, Verner-Jeffreys & Baker-Austin (2011) suggest research is needed to understand its impacts in comparison to far more dominant sources of resistant bacteria, particularly sewage treatment works.

While data on the environmental and human health effects of antibiotics used in aquaculture is limited, concerns raised by research so far would further support their prudent use, as in other veterinary and human medicine applications.

Anti-parasitics

Pesticides are usually used to remove parasites, such as sea lice. Sea lice are skin- and blood-eating parasites that can lead to death of fish and are a particular problem in salmon farming. However, the over-reliance on some pesticides in the first decade of the 21st century — for example, Slice®, with emamectin benzoate — has led to increased sea-louse tolerance to the drug, and a consequent decline in its use (Igboeli, 2012).

Such anthropogenic chemicals can also have negative effects on non-target species. Significant mortality has been recorded for the spot prawn (*Pandalus platyceros*) under laboratory conditions, at a concentration of 0.1 mg/kg, which was representative of the levels present in the benthic environment at salmon farms during the study's application period (Veldhoen *et al.*, 2012). A study has also looked at the effects of anti-louse pesticide formulations AlphaMax® (active ingredient: deltamethrin), Salmosan® (a.i.: azamethiphos) and Interox®Paramove™50 (a.i.: hydrogen peroxide) on the American lobster (*Homarus americanus*) and two types of shrimp, after short-term exposure periods of 1 hour or 24 hours: durations considered to be more representative of single exposures during commercial aquaculture treatments than durations used in previous studies.

Researchers found that behavioural responses were observed in all tests, often at concentrations much lower than the threshold estimate. Salmosan® and Interox®Paramove™50 were lethal to the non-target organisms tested at concentrations quite close to the recommended treatment concentration. AlphaMax®, however, was lethal at concentrations far below the recommended treatment concentration. It is also the only formulation of the three that is effective against all life stages of the sea lice. Deltamethrin, the active ingredient, can persist in sediment for weeks, and exposure of non-target species from a single cage treatment may occur via sediment, through ingestion of contaminated organic particles, as well as from water. (Burridge *et al.*, 2014)

Risks associated with these formulations are dependent on a number of factors and there are substantial differences between the environmental characteristics and hydrographic conditions of fish farm sites and their ability to accept discharges of sea-lice treatments without giving rise to unacceptable environmental impacts (Haya *et al.*, 2005). Studies are ongoing to assess the longer-term, sub-lethal effects and generate models of dispersion for some of these chemicals.

Managing pharmaceutical pollution: vaccines and sanitation

A site's assimilative capacity for pharmaceuticals may also be assessed using computer models, as with nutrient pollution. However, vaccines and sanitation are key to reducing the amount of antibiotics and anti-parasitics used (Serrano, 2005).

Norway provides an important example of how to successfully lower antibiotics use. Midtlyng, Grave & Horsberg (2011) report that antibiotics use has dropped by 90% in Norwegian salmon and brown trout cage farming since the 1980s, even though production has more than doubled in that time. This is mainly thanks to new vaccines which are used to control several major bacterial diseases (Grottum & Beveridge, 2007). Ongoing development and adoption of new vaccines can thus continue to play an important role in reducing the potential risks associated with antibiotics.

Fallowing (leaving pens to lie empty for a period) for over 3 months and allowing 5 km between sites has also helped keep the bacterial disease salmon anaemia under control in Norway (Grottum & Beveridge, 2007).

The use of anti-parasitics has also fallen thanks to increased use of more environmentally-friendly methods. For example, 'cleaner fish' also reduce the need for anti-parasitics. These are small fish, often wrasse, kept alongside farmed salmon to eat harmful lice. Skiftesvik *et al.* (2013) found that a ratio of 5 wrasse to 100 salmon on a Norwegian farm was enough to reduce pre-adult and adult lice numbers from an average of nine per fish to less than one.

Vaccines are expected to play a key role in reducing pesticide use, and are currently in development to protect fish against sea lice (Carpio *et al.*, 2011; 2013).

Langford *et al.* (2014) highlighted the need for international Environmental Quality Standards (EQSs) for anti-parasitics and said that a lack of monitoring and toxicity data makes it difficult to determine the risk of these pesticides to the marine environment. In their study, they found that usage of anti-parasitics on five Norwegian fish farms caused local water pollution which exceeded UK EQS thresholds. They referred to UK EQSs, as none are used in Norway[15].

1.3 Antifoulants

Antifoulants are chemicals applied to aquaculture equipment, such as cages and ropes, to reduce 'biofouling' — the unwanted growth of plants or creatures, such as barnacles, on their surface. Controlling biofouling is one of the most challenging — and expensive — production issues for the industry.

Most antifoulants use copper as their active ingredient, which can leach into the environment. Its toxic effects on various non-target species have been documented. For instance, it has found to reduce growth and reproduction levels in clams (Munari & Mistri, 2007), damage gills of fish (Mochida *et al.*, 2006) and inhibit phytoplankton growth (Cid *et al.*, 1995; Franklin, Stauber & Lim, 2001).

It can also contaminate seafloor sediment around farms. For example, a study of a Scottish salmon farm found copper in sediment up to 300 metres away from the cages (Dean, Shimmield & Black, 2007). The highest concentration detected, 805 micrograms of copper per gram of sediment ($\mu g\ g^{-1}$), was well above Scottish regulatory limits of 270 $\mu g\ g^{-1}$ and indicates adverse benthic effects.

'Booster' biocides are added to copper-based antifoulants, to increase their effectiveness. Several studies have found that most of these boosters can also be damaging to non-target species. For example, the herbicide cybutryne (a WFD priority substance) used to control algal growth also inhibits growth of other important species including sea grasses (Chesworth, Donkin & Brown, 2004) and corals (Owen *et al.*, 2002).

15. Of the five anti-parasitics considered in the study, one also has an EQS under EU legislation: cypermethrin is regulated under the WFD at 8 x 10 μg/litre (annual average) compared with 0.05 ng/litre in the UK.

Management techniques and new antifoulants

Negative impacts of antifoulants have fallen over the years, with more efficient products and usage (IUCN, 2007). However, farm management techniques to reduce antifoulant use continue to play an important role in sustainable aquaculture.

Fitridge *et al.* (2012) outline various biofouling management techniques that require no antifoulants. These include exposing fouled equipment to air, power washing, soaking marine equipment in freshwater and applying heat. The efficacy of each of these methods depends on the target species. Frequently changing and washing nets is widely practiced, but is costly and labour-intensive.

'Cleaner fish', used to control parasites (see section 1.2), can also reduce biofouling. They are less effective at controlling lice if nets are heavily fouled, however (Deady, Varian & Fives, 1995).

A number of non-toxic alternatives to copper-based antifoulants are in development. Many take inspiration from nature and use natural chemicals extracted from marine organisms, such as sponges and corals, that keep their own surfaces free of biofouling, as explored by Qian, Xu & Fusetani (2009). It is presently near impossible to produce these on a large, commercial scale, however, partly because it is not sustainable to harvest the source species from the wild.

Qian, Xu & Fusetani (2009) suggest that compounds from microorganisms, such as marine bacteria and fungi, offer a more promising solution. They say that a better understanding of the basic biology of fouling organisms including their genes and proteins, is also needed, so that new antifoulants can be developed that only affect these target species. The EU CRAB project[16] concluded that non-stick silicon surfaces and nanotechnology-based antifoulants in development offer some promise as alternatives to copper-based substances (CRAB, 2007). It also suggested that spiky coatings for aquaculture equipment could be considered. These would avoid the need for any chemicals.

1.4 Clean water for aquaculture

Environmental legislation is important in ensuring that water entering farms does not contaminate products with pathogens or contaminants — thus ensuring that products are safe to eat. One particular concern is water-borne microbes which may lead to food poisoning if contaminated shellfish are consumed.

Research has also highlighted the potential risk of contamination by toxic substances including polyaromatic hydrocarbons (PAHs), pesticides, polybrominated diphenyl ethers (PBDE), heavy metals and polychlorinated biphenyls (PCB). Some studies have found many of these substances at higher levels in farmed fish than in wild fish (discussed in Cole *et al.*, 2009), while recent data show that, in Europe, farmed salmon and trout typically contain lower levels of dioxins and PCBs than wild-caught salmon and trout, (see '**Managing seafood contamination**' below).

Managing seafood contamination

Various EU policies are relevant to seafood contamination from environmental pollution. The Shellfish Waters Directive[17] had considered water quality for shellfish production specifically, but was repealed in 2013.

However, other water-related regulations maintain the same level of protection as the Shellfish Waters Directive, which is required by the WFD. This objective, together with the necessary measures, should be reflected in WFD river basin management plans. Also relevant to ensuring good water quality for shellfisheries are the Bathing Water Directive[18] and the Urban Waste Water Directive[19], which address pollution from sewage. Further, the MSFD requires Member States to ensure that contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards.

The WFD encourages a joined-up approach to managing water quality which will benefit aquaculture by considering wider, river basin influences on both fresh- and marine waters.

The wide range of environmental factors that influence microbial water quality must be considered under this approach. Campos, Kershaw & Lee (2013) discuss influences on bacterial pathogens and indicator organisms, such as Enterococci and *E. coli*. These originate from human sewage and animal faeces and enter waterways from

16. http://www.crabproject.com
17. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:376:0014:0020:EN:PDF
18. http://ec.europa.eu/environment/water/water-bathing/index_en.html
19. http://ec.europa.eu/environment/water/water-urbanwaste/index_en.html

wastewater treatment works, run-off from agricultural land, sewage and storm tank overflow and boat discharge, among sources.

Recent data show that, in Europe, farmed salmon and trout typically contain lower levels of dioxins and PCBs than wild-caught salmon and trout, contrary to earlier studies (European Food Safety Authority, 2012). This improvement may reflect the requirement in the EU's Directive on undesirable substances in animal feed[20] for fishmeal and fish oil to be routinely tested (since 2005/2006) for contaminants. To meet this requirement, fishmeal may be decontaminated or producers can choose fishmeal species from cleaner waters (Oterhals & Nygård, 2008). Greater use of vegetable alternatives in feed (see section 2.3) may also reduce levels of some contaminants, such as mercury, although Berntssen, Julshamn & Lundebye (2010) warn that it could also increase levels of others, such as PAHs.

The contamination of fishmeal species (European examples include sprat and herring) clearly reflects general marine pollution in fishing areas. This can only be truly addressed on a much larger scale, as part of wider efforts to reduce environmental pollution.

Future prospects for aquaculture include relocating farms to offshore sites where water quality is more likely to be good. See Box 3 for details.

20. http://europa.eu/legislation_summaries/food_safety/animal_nutrition/l12069_en.htm

BOX 3.

Is the future of marine aquaculture offshore? Environmental issues considered

Marine aquaculture is predicted to move further out to sea in future, owing to competition for coastal space. Holmer (2010) concludes that it is difficult to predict the exact environmental impacts of this, as scientific knowledge is lacking. However, she highlights the following in her analysis:

- Nutrients would disperse more widely offshore, lowering their impact. Some seabed ecosystems could still be negatively affected by organic waste, however.
- There would be less chance of farmed fish interacting with coastal wildlife, and less risk of disease and parasite infections.
- The risk of fish escaping from pens could increase, as conditions are much rougher in the open ocean.
- As with all farms, it is important to site offshore farms away from sensitive seabed habitats and important migration routes for wild fish and mammals, to avoid unwanted ecological interactions.

Troell *et al.* (2009) caution that offshore farms are likely to be much larger than today's coastal farms, and produce more waste. Even in the open ocean, assimilative capacities can still be exceeded by nutrient pollution, they warn.

There is much interest in integrating aquaculture with offshore wind farms. Growing bivalves and/or seaweed on and around turbines would further reduce competition for space and offshore water quality is particularly good for shellfish. Trials in 2010 at a UK offshore wind farm showed that seabed mussel cultivation can be carried out using existing technologies and methods, and without causing any negative impacts on wind farm operators (Syvret *et al.*, 2013).

Elsewhere, farming mussels and seaweed on wind farms in the German North Sea would be both feasible and 'sufficiently profitable', according to Buck *et al.* (2008) and Buck, Ebeling & Michler-Cieluch (2010).

2. Ecological interactions

Farmed species and wild species can interact with each other in various ways. Concerns have been voiced about possible negative impacts of farmed species on natural ecosystems. This chapter considers the impacts of escapee fish (section 2.1), disease (section 2.2) and gathering wild species for aquaculture use (section 2.3).

It is important to note that aquaculture can also have positive ecological impacts. Pond farming of carp, common in central and eastern Europe, has been highlighted as an example of this. See Box 4 for discussion.

Box 4.

Environmental benefits of fishponds

Pond farming in Europe dates back to medieval times. It is typically extensive or semi-intensive, with fish living in a natural-like environment in either human-made or natural ponds. Due to its environmental benefits, it is often considered particularly suitable for Natura 2000 sites (European Commission, 2012).

Polish researchers have highlighted carp fishponds' value in creating habitat for many plants and animals and in retaining nutrients, with benefits for water quality as well as water flow (Cieśla, Błaszczak & Lirski, 2009). The ponds' ecological function can be similar to wetlands' and they are particularly attractive to birds.

Turkowski & Lirski (2011) estimated that ecosystem services provided by Polish carp ponds, such as flood protection (and not including food provision), could be worth as much as €3.7 billion in total. They stress that this is a preliminary valuation. For comparison, the total value of carp produced in Poland in 2011 was €29 million (European Commission, 2014c).

2.1 Escapees

Fish can escape from farms as a result of human error during handling, mechanical failure or damage to pens by weather or predators, such as seals and dolphins. Escapes are more likely to occur from open farms than closed farms.

Interbreeding with wild species: genetic impacts

Some species of escaped fish may breed with wild fish. Farmed fish typically have different genetic characteristics to their wild counterparts, often as a result of selective breeding for qualities such as high growth and low aggression. These traits also reduce their ability to survive and breed in the wild, however, and may be passed on to wild hybrid offspring if they do manage to breed.

For example, research in Ireland (McGinnity *et al.*, 2003) found that escapee Atlantic salmon and wild hybrids had only 27–89% of the lifetime success of wild salmon (i.e. they died young). Seventy per cent of second generation embryos died. These results suggest that interbreeding could lead to the extinction of vulnerable salmon populations.

Genetic mixing can also occur if fish release fertilised eggs from open farms into surrounding waters, i.e. even when no fish escape. This has been referred to as 'escape by spawning' by Jørstad *et al.* (2008), who found that 20–25% of wild cod larvae in the area surrounding a cod farm in Norway could be genetically traced back to 1000 spawning fish on the farm.

Similarity with local populations increases the risk of interbreeding. Naylor *et al.* (2005) point out that farmed Atlantic salmon find it much easier to breed with wild salmon when within their native range, such as in Norwegian, Irish and UK waters.

However, dissimilarity to local wild populations also increases genetic impacts. Danancher & Garcia-Vazquez (2011) assessed the potential risks of interbreeding among farmed and wild flatfish — a sector of aquaculture that is expected to grow significantly in future. They suggest that genetic impacts are more likely if: (1.) farmed populations are genetically distinct from native wild populations and/or

(2.) native wild populations are structured — that is, they contain sub-populations that each has a distinct genetic profile. Flounder and common sole, for example, have very structured populations. In this case, they recommend that local fish are used to breed stock (the 'broodstock') in flatfish farming. Triantafyllidis *et al.* (2007) write that the local population's suitability for broodstock depends on the species in question.

Invasive alien species

Aquatic invasive species pose a major threat to marine and freshwater ecosystems. Aquaculture is a source of invasive species which can compete with wild populations for food and space and spread disease. Katsanevakis *et al.* (2013) estimated that aquaculture is responsible for 16.4% of all marine invasive species in Europe, or 206 of 1369 species. It is the third biggest route for introduced species in European seas after shipping (which accounts for 51.9% of introductions through ballast water and hull fouling) and artificial marine and inland corridors (primarily the Suez Canal), which create new connections between habitats (40.3%)[21].

The study notes that the number of introductions via aquaculture halved during 2001–2010, compared with 1991–2000, dropping from 33 introduced species to 17. This is thanks to compulsory regulations and measures implemented at national or European level. The Regulation on the use of alien and locally absent species in aquaculture, for example, requires that approval to introduce a non-native species is supported by a risk assessment. Aquaculture is hailed by the study as 'the only success story' in efforts to halt marine introductions.

Work is also needed to address the accidental introduction of pest species with transfers of shellfish for farming. For instance, Mineur *et al.* (2014) calculated that non-native species from the Pacific Ocean were introduced to Europe at a steady rate of 1.16 per year between 1966 and 2010 as 'hitchhikers' on imports of both adult and young Pacific oysters for aquaculture. Some of these have come to be particularly invasive, such as the Japanese wireweed (*Sargassum muticum*).

Introduced species do not necessarily need to escape farms to spread disease — see section 2.2 for further discussion of aquaculture and diseases.

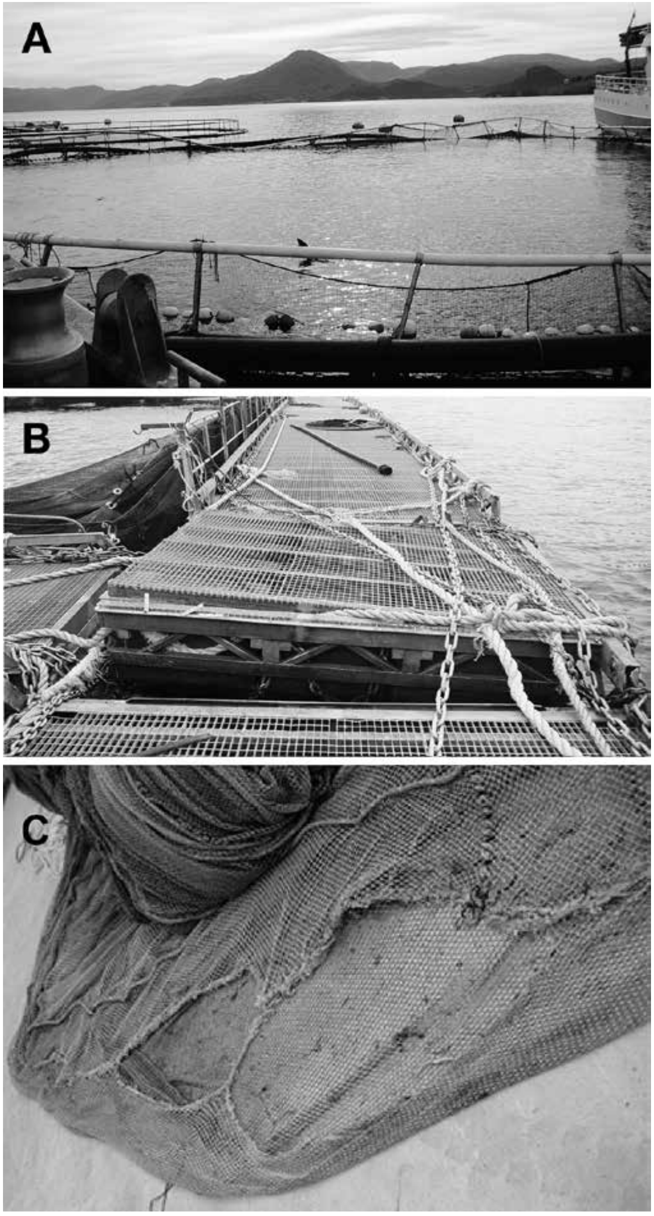

Figure 2: Examples of the major structural causes of escape incidents from Norwegian cage farming:
(A) progressive mooring failure; (B) breakdown and sinking of steel fish farms; and (C) abrasion and tearing of nets. Source: Jensen *et al.*, 2010.

21. Percentages add to more than 100% as some species are linked to more than one pathway.

Managing escapes

Scientific evidence and research will play an important role in helping Member States meet the objectives of policies related to the management of escape fish, including introduced species.

Introduced species in aquaculture are regulated under the Regulation on the use of alien and locally absent species in aquaculture and the new Regulation on the prevention and management of the introduction and spread of invasive alien species also applies.

The MSFD provides the option to Member States to use maritime spatial planning as a tool to support the ecosystem-based approach to managing human activities at sea. This means protecting the natural resources, such as wild fish stocks, that form the basis of the various activities.

Extensive research has been conducted into escapes from Norwegian fish farms. In 2006, 921 000 salmon (0.35% of caged stock) escaped from farms in Norway, according to official figures. By 2009, there were less than 200 000 escapees — just 0.07% of caged stock at the time (reported in Jensen *et al.* (2010)). This was largely thanks to new regulations for the design, installation and operation of sea-cage farms, according to Jensen *et al.* (2010).

The study's authors recommend a five-component strategy to managing escapes, based on Norway's experiences, which is applicable to other countries and farmed species: (1.) set up mandatory reporting of all escape incidents; (2.) establish a means of analysing and learning from the mandatory reporting; (3.) mandatorily assess the causes of escape involving more than 10 000 fish; (4.) introduce a technical standard for sea-cage aquaculture equipment, together with a means of enforcing the standard; and (5.) conduct mandatory training of fish farm staff in techniques to prevent escape.

The EU GENIMPACT project[22] highlighted several knowledge gaps relating to escapee aquaculture species which, if filled, could further help to manage aquaculture's ecological impacts (GENIMPACT, 2008). Research on escapees is heavily weighted towards Atlantic salmon, and there is still little information on the potential effects of interbreeding for most other species. A better understanding of wild spawning sites and migration routes would also enable farms to be sited better, away from sensitive areas.

GENIMPACT's guidelines for managing aquaculture's genetic impacts (Triantafyllidis *et al.*, 2007) emphasise the importance of understanding escape risk on a per-species basis; the biology of salmonids (fish in the salmon family, including trout) is generally unlike other groups of species.

While efforts must be made to reduce the number of escapes, the project acknowledges that it is impossible to completely prevent them. It thus suggests that the debate also revolves around the question of what *level* of escape should be regarded as a threat to wild populations? Namely, how many individuals can escape before their negative effects on natural stocks are noticeable?

GENIMPACT also recommended sterilising farmed species, or reducing their fertility, to eliminate opportunities for breeding with wild populations. There are several potential methods for achieving this. One already in use is 'triploidy', which increases the number of a fish's chromosome sets from two to three by 'shocking' fertilised fish eggs: with high pressure or heat, for example. It is not 'genetic modification', as DNA sequences are not altered.

2.2 Diseases

Disease can pass between wild and farmed species, and this area is regulated under EU animal health law[23]. This section focuses on the ecological impacts of disease spread by aquaculture species to wild populations.

Peeler *et al.* (2011) write that most cases of new diseases in European native, wild species are introduced by non-native, aquaculture species. For example, the parasite *Anguillicoloides crassus*, which was introduced to Europe through imported Asian eels from Japan to Germany, now infects wild European eels across many countries. It spread even though farmed eels did not escape and is thought to have contributed to European eels' dramatic decline over the last 20 years, together with other factors including habitat loss, pollution, fisheries, predators and obstacles to migration, such as hydropower.

22. http://www.imr.no/genimpact/en
23. Council Directive concerning the animal health conditions governing the placing on the market of aquaculture animals and products: http://ec.europa.eu/food/animal/animalproducts/aquaculture/index_en.htm

Sea lice

A subject of much debate in aquaculture is the question of as to what extent the spread of sea lice from sea cages with farmed salmonids affects wild salmonid populations. Intensive salmon farms provide good conditions for sea lice growth and transmission, compared with the wild environment, and outbreaks of this parasite are one of the biggest problems for operators.

According to some studies, patterns of lice outbreaks in wild fish in Ireland, Scotland, Norway and Canada appear to be linked with the heavy presence of salmon farms (Naylor, Eagle & Smith, 2003; Krkošek, Lewis & Volpe, 2005; Krkošek *et al.*, 2013).

Torrissen *et al.* (2013) write that salmon farms undoubtedly have strong effects on the local abundance of some parasites; however, it is difficult to quantify the specific impact on wild populations, owing to the many complex factors which affect population levels of wild anadromous salmonid species (those that migrate from the sea to freshwaters to spawn).

Some evidence suggests that wild population sizes in Norway have generally declined at a greater rate in areas where there are high numbers of open coastal salmon farms close to rivers (along which salmon migrate) (Otero *et al.*, 2011). Sea lice from farms, as well as negative effects of interbreeding (see section 2.1), may have contributed to this decline. These findings reinforce the importance of siting farms carefully and of developing new methods of managing sea lice.

Disease management

Peeler *et al.* (2011) call for improved risk mitigation to reduce the spread of disease from introduced aquaculture species. They suggest that transporting fish when they are just fertilised eggs, as opposed to live animals, reduces the risk of introducing exotic disease.

Costello (2009) suggests that good siting of salmon farms and coordinated fallowing between farms can reduce the risk of sea lice transmission. In some regions, lower farm density would further reduce risks.

Cleaner fish have been found to be a robust method for controlling salmon lice (as discussed in section 1.2). Using this method, species such as wrasse live alongside caged salmon and eat the lice. Vaccines are currently in development to protect against sea lice (Carpio *et al.*, 2013; 2011), which are shown to reduce infection rates and may form part of the solution, whilst reducing potential environmental risks associated with medication for fish (also as discussed in Section 1.2).

Sea lice will probably always be a problem for caged salmon and multiple strategies are needed to control this parasite to manageable levels and limit its ecological impact. Reviewing the evidence, Torrissen *et al.* (2013) say this will need a substantial increase in research into new pharmaceuticals, mechanical lice removal, vaccines, selective breeding for increased resistance, effective aquaculture production and use of cleaner fish, and the development of computer models which assess the risk of spread between sites and populations to help operators choose suitable sites and coordinate management.

2.3 Wild species collection

Wild fish for feed

Marine finfish species, such as salmon, sea bass and sea bream, are among the most popular seafood products with EU consumers (see Tables 1a and 1b). These marine finfish, which account for around 25% of EU production in volume (see Table 1b), are carnivorous and wild stocks of smaller fish are caught in large quantities for their feed. Naylor *et al.* (2000) commented that aquaculture is, paradoxically, “a possible solution, but also a contributing factor, to the collapse of fisheries stocks worldwide”.

The MSFD’s requirement to maintain populations of commercial fish “within safe biological limits” and the Common Fisheries Policy's objectives of ensuring that fisheries and aquaculture activities are environmentally sustainable and of “restoring and maintaining populations of fish stocks above biomass levels capable of producing maximum sustainable yield” are relevant in this respect, both in terms of its potential to reduce pressure from fishery activities, and the need to ensure that smaller fish fed to carnivorous farmed fish are sourced sustainably.

Environmental impacts of harvesting fish for feed in European seas can include: seabed damage caused by trawling, e.g. for sand eel and Norwegian pout, and disruption of ecosystems and food chains — reducing prey for other fish and seabirds (discussed in Huntington, 2009). Naylor *et al.* (2000) argued that captures of sand eel and pout in the North Sea, mainly for fishmeal, have contributed to wild cod's decline.

In 2005, aquaculture in Europe (including both EU and non-EU countries) consumed around 615 000 tonnes of fishmeal and 317 000 tonnes of fish oils per year; studies suggest that this required around 1.9 million tonnes of fish (Huntington, 2009). Total European aquaculture production at that time was of around 1.9 million tonnes (source: Eurostat[24]).

In recent years, wild fish have come to be used much more efficiently in feed. The ratio of wild fish input (via feed) to total farmed fish output fell by more than one-third between 1995 and 2007, from 1.04 to 0.63 (Naylor *et al.*, 2009). Up to 25% of fish meal now comes from fish processing waste, and fish content is substituted in part by vegetable oils. Improving feed efficiency is already a priority for the aquaculture industry as feed is the biggest production cost for operators.

Welch *et al.* (2010) argue that farmed marine finfish are a more efficient source of protein for humans, in terms of their consumption of marine resources, than wild-caught finfish. It is important that their feed is sustainably sourced and managed for these benefits to be realised.

However, with the expected expansion of aquaculture, there is an urgent need to further reduce the percentage of wild fish in feed and, most importantly, the total amount of wild fish consumed (should demand for feed rise significantly under aquaculture expansion). The effects of climate change are expected to lead to a global growth of wild fishmeal catches of around 3.6% of by 2050 (fished at around maximum sustainable yield levels), according to Merino *et al.* (2012). Even including this potential rise, current and projected future human consumption rates of seafood can only be sustained if aquaculture reduces its use of wild fish for feed. They estimate that the amount of fish used in feed to produce one unit of output would have to be reduced by at least 50% from current levels for aquaculture to be sustainable in 2050. This is 'theoretically feasible', the study suggests.

Tacon, Hasan & Metian (2011) write that the global supply of nutrients and feed will have to grow at a rate of around 8–10% per year to 2025, to match the aquaculture sector's growth rate.

Reducing dependency on wild stock for feed

Where fish continue to be harvested for feed, the IUCN (2007) has called for all feed fish to be certified as sustainable in future, to avoid damaging the environment. The Global Standard and Certification Programme for the Responsible Supply of Fishmeal and Fish Oil[25] has been developed by IFFO, the fishmeal industry association, to promote sustainability, as well as safety, among feed producers.

Tacon & Metian (2009) write that fishmeal and fish oil content of feed will need to be further substituted with alternative sources of nutrients. Vegetable sources already being used as a partial substitute include sunflower and linseed (Naylor *et al.*, 2009). However, they do not contain the omega-3 fatty acids they need as part of their diet.

A number of possible sources are being considered for plant-based substitutes, including single cell oils, which are extracted from marine microorganisms. For instance, Miller, Nichols & Carter (2007) report that thraustochytrids, a group of marine microorganisms, can be used to replace fish oil in the diets of juvenile Atlantic salmon without any apparent detrimental effects on fish health.

24. Eurostat http://ec.europa.eu/eurostat/statistics-explained/index.php/Main_Page
25. http://www.iffo.net/iffo-rs-standard

TABLES 1a and 1b

Top 10 aquaculture species in the EU, by value and volume.

Source data: Eurostat and EUMOFA. Source: European Commission (2014c).

1a Top 10 aquaculture species in the European Union (2011)
(value in thousands of EUR and percentage of total)

	value	% value
Salmon	752 116	20.90%
Trout	499 904	13.89%
Oyster	438 512	12.18%
Mussel	428 773	11.91%
Gilt-head seabream	370 251	10.29%
Seabass	369 812	10.28%
Clam	171 597	4.77%
Bluefin tuna	145 374	4.04%
Carp	136 467	3.79%
Turbot	70 949	1.97%

1b Top 10 aquaculture species in the European Union (2011)
(volume in tonnes live weight and percentage of total)

	volume	% volume
Mussel	492 413	39.18%
Trout	185 539	14.76%
Salmon	170 591	13.57%
Oyster	98 751	7.86%
Carp	73 860	5.88%
Gilt-head seabream	72 900	5.80%
Seabass	67 809	5.40%
Clam	37 028	2.95%
Other freshwater fish	13 989	1.11%
Turbot	10 799	0.86%

Source data: Eurostat and EUMOFA. Source: European Commission (2014c).

Naylor *et al.* (2009) write that single cell oils could completely replace fish oils in feed in the future, but they are expensive to produce and so currently uneconomical. The demand for fish oil, rather than fishmeal, is likely to determine the aquaculture sector's absolute demand for marine resources in future. Fish oil demand therefore plays a critical role in the impact of aquaculture on wild fish stocks.

While current market forces promote the production of carnivorous fish, Naylor *et al.* (2000) recommend that governments encourage more farming of herbivorous/omnivorous fish, such as carp and tilapia. At the global level, carp species are the main species of farmed finfish; non-fed species, including filter-feeding carps and bivalve shellfish, represented 31% of global aquaculture production in volume in 2012 (FAO, 2014).

Wild species for seed: the case of mussels

Mussel farming relies on gathering seed from the wild, which are then transferred to farms for growth and harvest. They are dredged from wild seed beds, scraped from rocks or collected from ropes.

Excessive collection can have negative ecological impacts. Camphuysen *et al.* (2002) linked the over-extraction of mussel seed (coupled with cockle fishing) in the early 1990s with the starvation of 21 000 eider ducks in 1999/2000 in protected coastal areas of the Dutch Wadden Sea, for instance.

Maguire *et al.* (2007) explored sustainable management of seed mussel beds in Ireland. They call for science-based approaches to exploiting seed and recommend that dredging should be carefully timed — at least two months after the last spawning to allow reproduction. Among other recommendations, annual surveys of seed beds should be conducted to inform management decisions. Beds that contribute significantly to larval production could be considered for protection and closed to fishing.

Mussel hatcheries have been proposed as a means of alleviating pressure on wild stocks. The technology to breed mussels in captivity is available, but is currently uneconomical (BLUE SEED, 2008). In general, hatcheries are used where other sources of seed are scarce, as with oysters and clams. The main benefit of hatcheries to shellfish farms would be to reduce the significant and unpredictable fluctuation in wild mussel seed stock.

Concluding remarks

Environmental concerns are already recognised by the aquaculture industry, which has made great progress in improving its environmental record in recent years. Research has shown that some environmental pressures can been mitigated in absolute terms, as seen with the dramatic reductions in escapees and antibiotics use in Norwegian salmon farms. Significant improvements in efficiency have also been noted, as with the reduction of wild fish used in feed. Technological and biological (through selective breeding) developments will enable further relative improvements, only if ecological interactions can be managed appropriately.

As the sector expands further, it must consider how to continually improve its environmental sustainability: this is essential to the long-term economic sustainability of aquaculture as well as to our food security.

Scientific evidence must continue to play a central role in this industry, informing best practice. Ongoing applied scientific research is needed to develop practical solutions to environmental problems. It is also clear that research into the very 'basics' of marine/aquatic ecology and processes is needed, from which better practical solutions can be developed.

Consumer demand and policy developments are also central in shaping the future of aquaculture. For instance, the MSP Directive is expected to improve the sustainability of aquaculture by considering when and where various human activities take place at sea. Member States will be required to carefully plan the co-location of marine activities, such as aquaculture, shipping and offshore energy, with the help of improved spatial data. This should ensure that all activities can benefit from synergies and that any negative environmental impacts can be minimised through their early identification.

Mussel farm, Primorsko, Bulgaria (CC BY 2.0) Vasil Raev, Flickr, 2013.

References

Abreu, M.H., Pereira, R., Yarish, C., Buschmann, A.H. & Sousa-Pinto, I. (2011) IMTA with *Gracilaria vermiculophylla*: Productivity and nutrient removal performance of the seaweed in a land-based pilot scale system. *Aquaculture* 312 (1-4): 77–87.

Bannister, R., Valdemarsen, T., PK, H., 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 (1): 29–47.

Berntssen, M.H.G., Julshamn, K. & Lundebye, A.-K. (2010) Chemical contaminants in aquafeeds and Atlantic salmon (*Salmo salar*) following the use of traditional-versus alternative feed ingredients. *Chemosphere* 78 (6): 637–646.

BLUE SEED (2008) BLUE SEED Final Report. Available from: http://www.blueseedproject.com/client/files/BLUE_SEED_Final_Report.pdf

Brennan, D. (2002) Pollution control options for Australian prawn farms. *Aquaculture Economics & Management* 6 (5-6): 325–338.

Buck, B.H., Ebeling, M.W. & Michler-Cieluch, T. (2010) Mussel cultivation as a co-use in offshore wind farms: potential and economic feasibility. *Aquaculture Economics & Management* 14 (4): 255–281.

Buck, B.H., Krause, G., Michler-Cieluch, T., Brenner, M., Buchholz, C.M., Busch, J.A., Fisch, R., Geisen, M. & Zielinski, O. (2008) Meeting the quest for spatial efficiency: progress and prospects of extensive aquaculture within offshore wind farms. *Helgoland Marine Research* 62 (3): 269–281.

Bureau, D.P. & Hua, K. (2010) Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. *Aquaculture Research* 41 (5): 777–792.

Burridge, L.E., Hamilton, N., Waddy, S.L., Haya, K., Mercer, S.M., Greenhalgh, R., Tauber, R., Radecki, S. V, Crouch, L.S., Wislocki, P.G. & Endris, R.G. (2004) Acute toxicity of emamectin benzoate (SLICE™) in fish feed to American lobster, Homarus americanus. *Aquaculture Research* 35 (8): 713–722.

Burridge, L.E., Lyons, M.C., Wong, D.K.H., MacKeigan, K., VanGeest, J.L. (2014) The acute lethality of three anti-sea lice formulations: AlphaMax®, Salmosan®, and Interox®Paramove™50 to lobster and shrimp. *Aquaculture* 420–421 : 180–186.

Camphuysen, C., Berrevoets, C., Cremers, H.J.W., Dekinga, A., Dekker, R., Ens, B., van der Have, T., Kats, R.K., Kuiken, T., Leopold, M., van der Meer, J. & Piersma, T. (2002) Mass mortality of common eiders (*Somateria mollissima*) in the Dutch Wadden Sea, winter 1999/2000: starvation in a commercially exploited wetland of international importance. *Biological Conservation* 106 (3): 303–317.

Campos, C.J.A., Kershaw, S.R. & Lee, R.J. (2013) Environmental Influences on Faecal Indicator Organisms in Coastal Waters and Their Accumulation in Bivalve Shellfish. *Estuaries and Coasts* 36 (4): 834–853.

Carl, J.D. (2014a) [Telephone conversation on KOMBI project]. (Personal communication, 2 December 2014).

Carl, J.D. (2014b). [Email: *Response to information of IMTA (aquaculture) in Denmark – Orbicon*]. (Personal communication, 6 December 2014).

Carpio, Y., Basabe, L., Acosta, J., Rodríguez, A., Mendoza, A., Lisperger, A., Zamorano, E., González, M., Rivas, M., Contreras, S., Haussmann, D., Figueroa, J., Osorio, V.N., Asencio, G., et al. (2011) Novel gene isolated from *Caligus rogercresseyi*: a promising target for vaccine development against sea lice. *Vaccine* 29 (15): 2810–2820.

Carpio, Y., García, C., Pons, T., Haussmann, D., Rodríguez-Ramos, T., Basabe, L., Acosta, J. & Estrada, M.P. (2013) Akirins in sea lice: first steps towards a deeper understanding. *Experimental Parasitology* 135 (2): 188–199.

Chesworth, J., Donkin, M. & Brown, M. (2004) The interactive effects of the antifouling herbicides Irgarol 1051 and Diuron on the seagrass *Zostera marina* (L.) *Aquatic Toxicology* 66 (3): 293–305.

Cid, A., Herrero, C., Torres, E. & Abalde, J. (1995) Copper toxicity on the marine microalga *Phaeodactylum tricornutum*: effects on photosynthesis and related parameters. *Aquatic Toxicology* 31 (2): 165–174.

Cieśla, M., Błaszczak, B. & Lirski, A. (2009) Traditional carp farming in Poland as an example of sustainable animal production. *Annals of Warsaw University of Life Sciences - SGGW, Animal Science* 46. pp. 329–337.

Coalition Clean Baltic (2014) Coalition Clean Baltic (CCB) position paper on principles and requirements for Sustainable Aquaculture in the Baltic Sea Region. Available from: http://www.ccb.se/documents/CCBSustainableAquaculturepositionpaperFINAL.pdf

Cole, D.W., Cole, R., Gaydos, S.J., Gray, J., Hyland, G., Jacques, M.L., Powell-Dunford, N., Sawhney, C. & Au, W.W. (2009) Aquaculture: Environmental, toxicological, and health issues. *International Journal of Hygiene and Environmental Health* 212 (4): 369–377.

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* 276 (1672): 3385–3394.

CRAB (2007) European Best Practice in Aquaculture Biofouling. Available from: www.crabproject.com/client/files/CRAB_Best_Practice_Guidelines.pdf

Danancher, D. & Garcia-Vazquez, E. (2011) Genetic population structure in flatfishes and potential impact of aquaculture and stock enhancement on wild populations in Europe *Reviews in Fish Biology and Fisheries* 21 (3): 441–462. [Accessed 27 May 2014].

Deady, S., Varian, S.J.A. & Fives, J.M. (1995) The use of cleaner-fish to control sea lice on two Irish salmon (*Salmo salar*) farms with particular reference to wrasse behaviour in salmon cages. *Aquaculture* 131 (1-2): 73–90.

Dean, R.J., Shimmield, T.M. & Black, K.D. (2007) Copper, zinc and cadmium in marine cage fish farm sediments: an extensive survey. *Environmental Pollution* 145 (1): 84–95.

European Commission (2012) Guidance on Aquaculture and Natura 2000. Available from: http://ec.europa.eu/environment/nature/natura2000/management/docs/Aqua-N2000 guide.pdf

European Commission (2013) Strategic Guidelines for the sustainable development of EU aquaculture. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Available from: http://ec.europa.eu/fisheries/cfp/aquaculture/official_documents/com_2013_229_en.pdf

European Commission (2014a) Farmed in the EU. Available from: http://ec.europa.eu/fisheries/images/aquaculture/aquaculture-infographics_en.pdf

European Commission (2014b) The EU Fish Market. Available from: http://ec.europa.eu/fisheries/market-observatory/documents/10157/bf18cf2c-1b33-440d-8870-e05b2644b58b

European Commission (2014c) *Facts and figures on the Common Fisheries Policy.* Luxembourg: Publications Office of the European Union. ISBN 978-92-79-34192-2 DOI: 10.2771/35745 Available from: http://ec.europa.eu/fisheries/documentation/publications/pcp_en.pdf

European Food Safety Authority (2012) Update of the monitoring of levels of dioxins and PCBs in food and feed 1. *EFSA Journal* 10 (7): 2832 [82 pp.]

FAO (2014) *The State of World Fisheries and Aquaculture 2014.* Rome: FAO. p.23. Available from: http://www.fao.org/3/a-i3720e.pdf

Ferreira, C.S.G., Nunes, B.A., Henriques-Almeida, J.M. de M. & Guilhermino, L. (2007) Acute toxicity of oxytetracycline and florfenicol to the microalgae *Tetraselmis chuii* and to the crustacean *Artemia parthenogenetica*. *Ecotoxicology and Environmental Safety* 67 (3): 452–458.

Fitridge, I., Dempster, T., Guenther, J. & de Nys, R. (2012) The impact and control of biofouling in marine aquaculture: a review. *Biofouling* 28 (7): 649–669.

Franklin, N.M., Stauber, J.L. & Lim, R.P. (2001) Development of flow cytometry-based algal bioassays for assessing toxicity of copper in natural waters. *Environmental Toxicology and Chemistry* 20 (1): 160–170.

GENIMPACT (2008) Evaluation of genetic impact of aquaculture activities on native populations - A European network. Available from: http://cordis.europa.eu/documents/documentlibrary/123869771EN6.pdf

Grottum, J.A. & Beveridge, M. (2007) A review of cage aquaculture: northern Europe. In M. Halwart, D. Soto and J.R. Arthur (eds). *Cage aquaculture – Regional reviews and global overview*: 126–154. FAO Fisheries Technical Paper. No. 498. Rome, FAO. pp 241 Available from: ftp://ftp.fao.org/docrep/fao/010/a1290e/a1290e06.pdf

Gyllenhammar, A., Håkanson, L. & Lehtinen, K.-J. (2008) A mesocosm fish farming experiment and its implications for reducing nutrient load on a regional scale. *Aquacultural Engineering* 38 (2): 117–126.

Haya, K., Burridge, L. E., Davies, I. M., Ervik, A. (2005) A Review and Assessment of Environmental Risk of Chemicals Used for the Treatment of Sea Lice Infestations of Cultured Salmon. *Environmental Effects of Marine Finfish Aquaculture*, 5M: 305–340.

Holdt, S. & Edwards, M. (2014) Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. *Journal of Applied Phycology* 26 (2): 933–945.

Holmer, M. (2010) Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. *Aquaculture Environment Interactions* 1 (1): 57–70.

Huntington, T. (2009) Use of wild fish and other aquatic organisms as feed in aquaculture – a review of practices and implications in Europe. In: Hasan, M.R.; Halwart, M. (eds). *Fish as feed inputs for aquaculture: practices, sustainability and implications*. FAO Fisheries and Aquaculture Technical Paper 518: Rome. pp. 209–268. Available from: http://www.fao.org/docrep/012/i1140e/i1140e05.pdf

Igboeli, O.O., Fast, M. D., Heumannc, J. & Burkaa J. F. (2012) Role of P-glycoprotein in emamectin benzoate (SLICE®) resistance in sea lice, *Lepeophtheirus salmonis*. *Aquaculture* 344–349: 40–47. doi:10.1016/j.aquaculture.2012.03.026

IUCN (2007) Guide for the Sustainable Development of Mediterranean Aquaculture. Interaction between Aquaculture and the Environment. Available from: https://cmsdata.iucn.org/downloads/acua_en_final.pdf

Jensen, Ø., Dempster, T., Thorstad, E., Uglem, I. & Fredheim, A. (2010) Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. *Aquaculture Environment Interactions* 1 (1): 71–83.

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. *Reviews in Fisheries Science* 16 (1-3): 285–295.

Katsanevakis, S., Zenetos, A., Belchior, C. & Cardoso, A.C. (2013) Invading European Seas: Assessing pathways of introduction of marine aliens. *Ocean & Coastal Management* 76: 64–74.

Krkošek, M., Lewis, M.A. & Volpe, J.P. (2005) Transmission dynamics of parasitic sea lice from farm to wild salmon *Proceedings of the Royal Society B* 272 (1564): 689–696.

Krkosek, M., Revie, C.W., Gargan, P.G., Skilbrei, O.T., Finstad, B. & Todd, C.D. (2013) Impact of parasites on salmon recruitment in the Northeast Atlantic Ocean. *Proceedings of the Royal Society B* 280 (1750): 20122359.

Langan, R. (2004) Balancing marine aquaculture inputs and extraction: Combined culture of finfish and bivalve molluscs in the open ocean. *Bulletin-Fisheries Research Agency Japan.* Supplement: 51–58.

Langford, K.H., Øxnevad, S., Schøyen, M. & Thomas, K. V (2014) Do Antiparasitic Medicines Used in Aquaculture Pose a Risk to the Norwegian Aquatic Environment? *Environmental Science & Technology* 48 (14): 7774–7780.

Maguire, J.A., Knights, T., Burnell, G., Crowe, T., O’Beirn, F., McGrath, D., Ferns, M., McDonough, N., McQuaid, N., O’Connor, B., Doyle, R., Newell, C., Seed, R., Smaal, A., et al. (2007) *Management recommendations for the sustainable exploitation of mussel seed in the Irish Sea.* Available from: http://oar.marine.ie/bitstream/10793/271/1/No%2031%20Marine%20Environment%20and%20Health%20Series.pdf

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* 270 (1532): 2443–2450.

Merino, G., Barange, M., Blanchard, J.L., Harle, J., Holmes, R., Allen, I., Allison, E.H., Badjeck, M.C., Dulvy, N.K., Holt, J., Jennings, S., Mullon, C. & Rodwell, L.D. (2012) Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change* 22 (4): 795–806.

Midtlyng, P.J., Grave, K. & Horsberg, T.E. (2011) What has been done to minimize the use of antibacterial and antiparasitic drugs in Norwegian aquaculture? *Aquaculture Research* 42: 28–34.

Miller, M.R., Nichols, P.D. & Carter, C.G. (2007) Replacement of fish oil with thraustochytrid Schizochytrium sp. L oil in Atlantic salmon parr (*Salmo salar* L) diets. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology* 148 (2): 382–392.

Mineur, F., LE Roux, A., Maggs, C.A. & Verlaque, M. (2014) Positive Feedback Loop between Introductions of Non-Native Marine Species and Cultivation of Oysters in Europe. *Conservation Biology*. DOI: 10.1111/cobi.12363.

Mochida, K., Ito, K., Harino, H., Kakuno, A. & Fujii, K. (2006) Acute toxicity of pyrithione antifouling biocides and joint toxicity with copper to red sea bream (*Pagrus major*) and toy shrimp (*Heptacarpus futilirostris*). *Environmental Toxicology and Chemistry* 25 (11): 3058–3064.

Munari, C. & Mistri, M. (2007) Effect of copper on the scope for growth of clams (*Tapes philippinarum*) from a farming area in the Northern Adriatic Sea. *Marine Environmental Research* 64 (3): 347–357.

Naylor, R., Hindar, K., Fleming, I.A., Goldburg, R., Williams, S., Volpe, J., Whoriskey, F., Eagle, J., Kelso, D. & Mangel, M. (2005) Fugitive Salmon: Assessing the Risks of Escaped Fish from Net-Pen Aquaculture. *BioScience* 55 (5): 427.

Naylor, R.L., Eagle, J. & Smith, W.L. (2003) Salmon Aquaculture in the Pacific Northwest A Global Industry with Local Impacts. *Environment: Science and Policy for Sustainable Development* 45 (8): 18–39.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. (2000) Effect of aquaculture on world fish supplies. *Nature* 405 (6790): 1017–1024.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrell, A.P., Forster, I., Gatlin, D.M., Goldburg, R.J., Hua, K. & Nichols, P.D. (2009) Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences* 106 (36): 15103–15110.

Oterhals, Å. & Nygård, E. (2008) Reduction of Persistent Organic Pollutants in Fishmeal: A Feasibility Study. *Journal of Agricultural and Food Chemistry* 56 (6): 2012–2020.

Otero, J., Jensen, A.J., L'Abée-Lund, J.H., Stenseth, N.C., Storvik, G.O. & Vøllestad, L.A. (2011) Quantifying the ocean, freshwater and human effects on year-to-year variability of one-sea-winter Atlantic salmon angled in multiple Norwegian rivers. Stuart Humphries (ed.) *PLOS ONE* 6 (8): e24005.

Owen, R., Knap, A., Toaspern, M. & Carbery, K. (2002) Inhibition of coral photosynthesis by the antifouling herbicide Irgarol 1051 *Marine Pollution Bulletin* 44 (7): 623–632.

Peeler, E.J., Oidtmann, B.C., Midtlyng, P.J., Miossec, L. & Gozlan, R.E. (2011) Non-native aquatic animals introductions have driven disease emergence in Europe. *Biological Invasions* 13 (6) p.pp. 1291–1303.

Petersen, J.K., Hasler, B., Timmermann, K., Nielsen, P., Tørring, D.B., Larsen, M.M. & Holmer, M. (2014) Mussels as a tool for mitigation of nutrients in the marine environment. *Marine Pollution Bulletin* 82 (1-2): 137–143.

Pittenger, R., B. Anderson, D.D. Benetti, P.D., B. Dewey, R. Goldburg, A. Rieser, B. Sher, and A. & Sturgulewski (2007) Sustainable marine aquaculture: Fulfilling the promise; managing the risks. Available from: http://www.pewtrusts.org/en/research-and-analysis/reports/2007/01/09/sustainable-marine-aquaculture-fulfilling-the-promise-managing-the-risks

Price, C.S. and J.A. Morris, J. (2013) Marine Cage Culture & The Environment: Twenty-First Century Science Informing a Sustainable Industry. Available from: http://www2.coastalscience.noaa.gov/publications/detail.aspx?resource=lS+q3d4eICvFWKFlXBYmz48uUqIGeFF871rIXjLV1/Y=

Qian, P.-Y., Xu, Y. & Fusetani, N. (2009) Natural products as antifouling compounds: recent progress and future perspectives. *Biofouling* 26 (2): 223–234.

Rigos, G., Nengas, I., Alexis, M. & Troisi, G.M. (2004) Potential drug (oxytetracycline and oxolinic acid) pollution from Mediterranean sparid fish farms. *Aquatic Toxicology* 69 (3): 281–288.

Saikku, L. & Asmala, E. (2010) Eutrophication in the Baltic Sea. *Journal of Industrial Ecology* 14 (3): 482–495.

Sanz-Lázaro, C., Belando, M.D., Marín-Guirao, L., Navarrete-Mier, F. & Marín, A. (2011) Relationship between sedimentation rates and benthic impact on Maërl beds derived from fish farming in the Mediterranean. *Marine Environmental Research* 71 (1): 22–30.

Sarà, G., Lo Martire, M., Sanfilippo, M., Pulicanò, G., Cortese, G., Mazzola, A., Manganaro, A. & Pusceddu, A. (2011) Impacts of marine aquaculture at large spatial scales: evidences from N and P catchment loading and phytoplankton biomass. *Marine Environmental Research* 71 (5): 317–324.

Serrano, P.H. (2005) Responsible use of antibiotics in aquaculture. FAO Fisheries Technical Paper. No. 469. Available from: ftp://ftp.fao.org/docrep/fao/009/a0282e/a0282e00.pdf

Skiftesvik, A.B., Bjelland, R.M., Durif, C.M.F., Johansen, I.S. & Browman, H.I. (2013) Delousing of Atlantic salmon (*Salmo salar*) by cultured vs. wild ballan wrasse (*Labrus bergylta*). *Aquaculture*. 402–403pp. 113–118.

Syvret, M., Fitzgerald, A., Gray, M., Wilson, J., Limited, A. S., Lane, H., & Ex, D. (2013). *Aquaculture in Welsh offshore wind farms: A feasibility study into potential shellfish cultivation in offshore wind farm sites.* Report for the Shellfish Association of Great Britain. Available from: https://dl.dropboxusercontent.com/u/51566819/Project%20Ref%20ID%2071%20-%20Co-location%20Project%20-%20Ver.%20FR1.1.pdf

Tacon, A.G.J. & Metian, M. (2009) Fishing for Aquaculture: Non-Food Use of Small Pelagic Forage Fish—A Global Perspective. *Reviews in Fisheries Science* 17 (3): 305–317.

Tacon, A.G.J., Hasan, M.R., Metian, M. (2011) *Demand and supply of feed ingredients for farmed fish and crustaceans.* FAO Fisheries and Aquaculture Technical Paper No. 564. Available from: http://www.fao.org/docrep/015/ba0002e/ba0002e00.htm

Taylor, N.G.H., Verner-Jeffreys, D.W. & Baker-Austin, C. (2011) Aquatic systems: maintaining, mixing and mobilising antimicrobial resistance? *Trends in Ecology & Evolution* 26 (6): 278–284.

KH-BB-14-004-EN-N

Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O.T., Nilsen, F., Horsberg, T.E. & Jackson, D. (2013) Salmon lice--impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases* 36 (3): 171–194.

Triantafyllidis, A., Karaiskou, N., Bonhomme, F., Colombo, L., Crosetti, D., Danancher, D., García-Vázquez, E., Gilbey, J., Svåsand, T. & Verspoor, E. (2007) *Management options to reduce genetic impacts of aquaculture activities. Genetic impact of aquaculture activities on native populations.* Genimpact final scientific report. pp. 161–174. Available from: http://www.imr.no/genimpact/filarkiv/2007/07/management_options.pdf/en

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H. & Fang, J.-G. (2009) Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297 (1-4): 1–9.

Turkowski, L., Lirski, A. (2011) Non-productive functions of fish ponds and their possible economic evaluation. In: A. Lirski, A. Pyć (ed.). *Chów karpia w Europie: Stan obecny, trudności, perspektywy* [Carp culture in Europe: Current status, problems, perspectives.]. IRŚ Olsztyn Press. pp. 274.

Valdemarsen, T., Bannister, R.J., Hansen, P.K., Holmer, M. & Ervik, A. (2012) Biogeochemical malfunctioning in sediments beneath a deep-water fish farm. *Environmental Pollution* 170: 15–25.

Veldhoen, N., Ikonomou, M. G., Buday, C., Jordan, J., Rehaume, V., Cabecinha, M., Dubetz, C., Chamberlain, J., Pittroff, S., Vallée, K., van Aggelen, G. & Helbing, C. C. (2012) Biological effects of the anti-parasitic chemotherapeutant emamectin benzoate on a non-target crustacean, the spot prawn (*Pandalus platyceros* Brandt, 1851) under laboratory conditions. *Aquatic Toxicology* 108: 94–105

Welch, A., Hoenig, R., Stieglitz, J., Benetti, D., Tacon, A., Sims, N. & O'Hanlon, B. (2010) From Fishing to the Sustainable Farming of Carnivorous Marine Finfish. *Reviews in Fisheries Science* 18 (3): 235–247.