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Towards cost-effective biofouling management in salmon aquaculture: a strategic outlook

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Abstract

Biofouling is an ongoing challenge for marine salmon aquaculture, impacting farming operations, fish health and welfare. Current mitigation strategies employed in Norway and Scotland rely mainly on the use of antifouling coatings and reactive removal of biofouling. These approaches are not only costly and of limited efficacy, but also pose active risks and likely contribute to mortality of fish during grow-out at sea. Given the inefficiencies of current biofouling management approaches and the industry's objectives for growth and sustainability, a strategic assessment of future avenues for biofouling management is needed. We here present such an assessment and outline three novel biofouling management strategies that, once implemented, could facilitate improved fish health and welfare, reduced environmental impacts and benefits to the public perception of fish farming. These strategies are based on: (i) efficient antifouling coatings; (ii) antifouling combined with intermittent cleaning; and (iii) grooming of nets. We discuss the advantages, challenges and research and development needs associated with the realisation of these strategies. Drawing on experiences from agricultural systems and invasive species management, we show how the costs involved in the implementation of new strategies will over time be offset by the direct and indirect benefits arising from a reduction in environmental and fish health impacts and an increase in the industry's social licence to operate.

Key words: antifouling, biofouling, economics, net cleaning, Salmo salar.

Biofouling in salmon aquaculture

Biofouling, the growth of organisms on submerged structures (Fig. 1), is a serious challenge for global marine salmon aquaculture (Fitridge *et al*. 2012; Bannister *et al*. 2019). The need and motivation for managing biofouling development on farming infrastructure arise from four major impacts that biofouling poses in the absence of intervention:

(1) *Occlusion of the pen net*. The presence of biofouling on the net hinders water exchange across the net, reducing waste removal and oxygen availability and thus degrading water quality (Cronin *et al*. 1999; Madin *et al*. 2010). Net occlusion also increases drag forces on the net, adding strain to mooring systems and deforming the pen net, effectively reducing its volume by up to 40% (Lader *et al*. 2008; Klebert *et al*. 2013; Swain & Shinjo 2014; Bi & Xu 2018), which can artificially increase stocking densities to potentially stressful levels (Oppedal *et al*. 2011b).

(2) *Increased disease and welfare risks*. Biofouling organisms can be harmful to farmed fish upon contact. For example, the nematocysts of cnidarians such as hydroids and anemones lead to gill and skin damage (Baxter *et al*. 2012; Fisher & Appleby 2017; Bloecher *et al*. 2018). Moreover, biofouling organisms can harbour pathogens, acting as reservoirs and vectors for diseases such as vibriosis (Pietrak *et al*. 2012), amoebic gill disease (Hellebø *et al*. 2016) or parasitic blood flukes (Shirakashi & Hirano 2015; Sugihara *et al*. 2015).

(3) *Altered behaviour of cleaner fish*. Biofouling organisms are among the natural food sources of lumpsucker and wrasse species that are used as biological control ('cleaner fish') against salmon lice in Norwegian and Scottish salmon farms (Kvenseth 1996; Imsland *et al*. 2015). Many farmers are concerned that cleaner fish reduce their delousing activity in the presence of biofouling as an alternative food source (Deady *et al.* 1995; Eliasen *et al.* 2018). This concern is possibly the strongest driver for biofouling mitigation on pen nets in Norway (Bouwman 2020). However, there is increasing uncertainty and controversy around the perceived interference of biofouling on cleaner fish performance (Eliasen *et al.* 2018; Leclercq *et al.* 2018) as well as the continuation of their use as control agents due to welfare concerns (Hjeltnes *et al.* 2019; Mo & Poppe 2019) and poor demonstrated efficacy at full commercial scale (Barrett *et al.* 2020; Overton *et al.* 2020).

(4) *Reservoirs for non-indigenous species (NIS)*. By offering settlement space on farm equipment, aquaculture sites can act as stepping stones for the range expansion of biofouling and other NIS which, in turn, may facilitate wider ecosystem impacts. In addition, the coordinated release of gametes during farming operations such as net cleaning can further facilitate their establishment in adjacent natural environments (Carl *et al.* 2011; Mineur *et al.* 2012; Simkanin *et al.* 2012).

Control of biofouling in Norwegian and Scottish salmon farms

Over the past decades, salmon farmers around the world have developed a range of approaches for addressing these biofouling challenges – usually at considerable cost and with mixed success (Bannister *et al* 2019). The objective of this article is to outline some strategic options for the future of biofouling management in Atlantic salmon (*Salmo salar*) aquaculture, using Norway and Scotland as case study regions. Norway and Scotland are among the world's main producers of farmed Atlantic salmon (featuring a total of >1000 active farming sites and a combined production of 1.4 million tonnes (Marine Scotland Science 2019; Norwegian Directorate of Fisheries 2020)), and their industries utilise similar operational practices with regard to biofouling management. Although there are slight differences in how biofouling is addressed in other farming regions (e.g. Chile, Australia and New Zealand; Bannister *et al.* 2019), many challenges are shared and our proposed approaches have global relevance.

Salmon farmers in Norway and Scotland currently concentrate on two main avenues of biofouling control: (i) prevention of biofouling development and (ii) biofouling removal.

Prevention of biofouling development

Prevention or minimisation of biofouling growth is primarily implemented using biocidal coatings on nets. Copper is the main biocide in use, supported (or sometimes replaced) by booster biocides such as copper pyrithione,

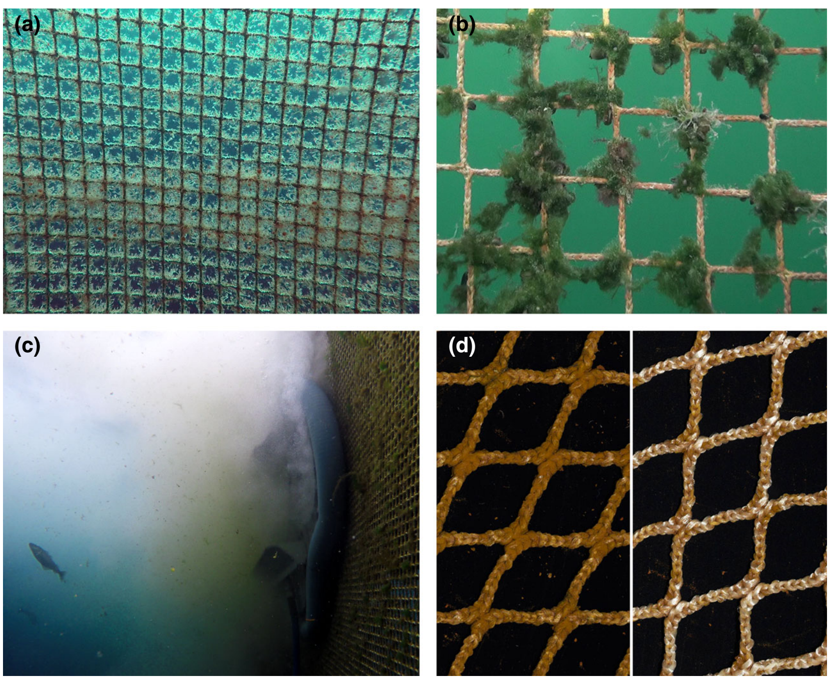


Figure 1 Examples of a nylon net fouled with (a) hydroids (photo: Mai-Louise Bouwman) and (b) algae. (c) Particles released during cleaning of a biofouled net; (d) a copper-coated nylon net before (left) and after (right) a single net cleaning event using a high-pressure cleaner resulting in abrasion damage of the red copper coating.

zinc pyrithione or tralopyril. The success of the coating depends on the combination and relative concentration of the biocides, as well as the biofouling pressure around the farming sites (Edwards *et al*. 2014; Bloecher & Floerl 2020). Protection rarely lasts for the entire duration of the marine grow-out phase (commonly 10–24 months) and can fail as early as 8 weeks following immersion (Bloecher & Floerl 2020). While biocidal coatings are common in salmon farming in Norway and Scotland, other salmon-producing countries such as Australia and New Zealand have largely phased out their use due to environmental concerns (Floerl *et al*. 2016; Bannister *et al*. 2019). Copper generally does not accumulate in the marketable tissue of farmed fish at levels that exceed food safety standards (Cotou *et al*. 2012; Nikolaou *et al*. 2014; Kalantzi *et al*. 2016), yet impacts on the health of fish (Burridge *et al*. 2010; Azizishirazi *et al*. 2015) and non-target organisms (Burridge *et al*. 2010; Thomas & Brooks 2010; Fitridge *et al*. 2012; Guardiola *et al*. 2012) occur.

As an alternative to antifouling coatings, copper alloy metal nets have shown success in limiting or preventing biofouling development (Chambers *et al*. 2012). However, due to high initial costs, weight and challenging handling, their use is still limited. While overall leaching rates are assumed to be lower, initial leaching rates can exceed those of copper-coated nets (Kalantzi *et al*. 2016).

Biofouling removal

Removal of biofouling is mainly implemented using in situ cleaning of pen nets. Net cleaning technology mostly relies on pressurised water expelled from rotating discs mounted onto a 'cleaning rig' that moves along the inside of pens and washes biofouling organisms off the nets (Fig. 1). The most common systems generate high-pressure cleaning jets of up to 350 bar, although lower-pressure cleaning (50–150 bar) in combination with higher water volumes is becoming more frequent (N. Bloecher, pers. obs.). While older cleaning units are attached to cranes or remotely operated vehicles (ROVs), newer systems are self-propelled and can be steered remotely from support vessels, similar to ROVs (Bannister *et al*. 2019). As an alternative to pressure-washing, cavitation- and brush-based systems have been developed (Bannister *et al*. 2019). However, they are not yet widely used, and their efficacy remains to be evaluated.

Currently, net cleaning on Norwegian salmon farms in biofouling-prone regions is conducted every two weeks or more frequently, depending on biofouling pressure (Bloecher *et al*. 2015; Floerl *et al*. 2016; Bannister *et al*. 2019). The development of autonomous net cleaning technology pursues increased cleaning frequencies or even continuous net cleaning (i.e. 'grooming') to prevent the establishment of mature biofouling communities.

Net cleaning is labour-intensive and costly (Table 1). It releases significant amounts of cleaning waste into the surrounding environment, depending on local conditions and season (Fig. 1c). The release of biofouling particles is presently the norm during net cleaning operations and presents a multitude of risks, including the transmission of associated fish pathogens (Andersen *et al*. 1993; Pietrak *et al*. 2012; Albert & Ransangan 2013; Hellebø *et al*. 2016), gill and skin damage to the fish (Baxter *et al*. 2012; Fisher & Appleby 2017; Bloecher *et al*. 2018), organic deposition and contamination below fish farms (Skarbøvik *et al*. 2017; Bloecher *et al*. 2019) and the spread of NIS (Floerl *et al*. 2016; Bannister *et al*. 2019). Exposure to net cleaning waste can be exacerbated by reduced water exchange in the upper parts of the net pen due to the widespread use of sea lice exclusion 'skirts' (Frank *et al*. 2015; Barrett *et al*. 2020; Klebert & Su 2020). Some pressure-washing systems have been combined with a suction unit, but their collection efficacy remains unclear and their use in Norwegian and Scottish salmon aquaculture is very limited. Fish farm operators report that net cleaning causes a loss of appetite in salmon, potentially leading to reduced biomass growth, and there is concern that stress induced by net cleaning may trigger

Table 1 Cost associated with traditional biofouling management on salmon farms in Norway consisting of a combination of net antifouling and cleaning, or frequent cleaning of uncoated nets

Item/activity	Cost per net pen/single cleaning operation (US$)	Cost per farm site and production cycle using coated nets (US$)	Cost per farm site and production cycle using uncoated nets (US$)
Copper AF coating	$ 30 200	$ 241 600	–
Net cleaning	$ 2100	$ 252 000	$ 420 000
Total cost		$ 493 600	$ 420 000

Values presented are averages collated from consultation with aquaculture companies and provide realistic estimates rather than absolute values. Per-farm costs are based on an average farm size (eight production pens) and an 18-month production cycle in a biofouling-prone region where nets are exchanged once, and net cleaning is conducted 15 times on coated nets and 25 times on uncoated nets. Personnel costs are not included (for detailed calculations see Supporting Information).

disease outbreaks. Moreover, anecdotal evidence indicates increased mortality among cleaner fish following net cleaning (Imsland & Nytrø 2017).

Net cleaning can inflict substantial damage on net coatings (Fig. 1d). Pressure-washing can remove up to 30% of the coating during the first cleaning event (Bloecher *et al.* 2019) and, together with leaching, results in up to 85% loss of the coating during a single service life, causing an annual release of more than 1000 tonnes of copper into Norwegian waters alone (Skarbøvik *et al.* 2017). While net cleaning per se does not impact the integrity of the net, incorrect use and insufficient maintenance of net cleaning equipment or the presence of other cage elements (e.g. ropes) that increase the friction of the net cleaner's rotating discs on the net can result in damage to the net (Moe Føre & Gaarder 2018; Bloecher *et al.* 2019), contributing to the risk of fish escapes.

Other (less common) approaches

To avoid net cleaning and the associated risks, regular exchange of nets is practised in some farms, especially if sites are farming 'organic' salmon or are certified according to the Aquaculture Stewardship Council (ASC) Salmon Standard that prohibits in situ high-pressure cleaning of biocidal coatings (Aquaculture Stewardship Council 2019). Uncoated nets need to be exchanged frequently during each production cycle depending on location and circumstances. The use of antifouling coatings can reduce this to approximately four to five times per production cycle. Although the exchange of nets avoids the release of cleaning waste, it entails other environmental challenges. One is the increased hazard of fish escaping during net exchange operations (Fredheim *et al.* 2010; Thorvaldsen *et al.* 2015; Føre *et al.* 2019) – a legal offence in Norway due to risks posed to wild salmon stocks. The other is the fact that exchanged nets featuring antifouling coatings need to be cleaned before they are re-coated and re-deployed. Cleaning of used nets is conducted in land-based washing facilities. While this ensures the collection of biocidal material (Norwegian Ministry of Climate & Environment 2004, amended 2016), additional coating abrasion during this process increases the overall biocide consumption during re-coating.

Current costs of biofouling management

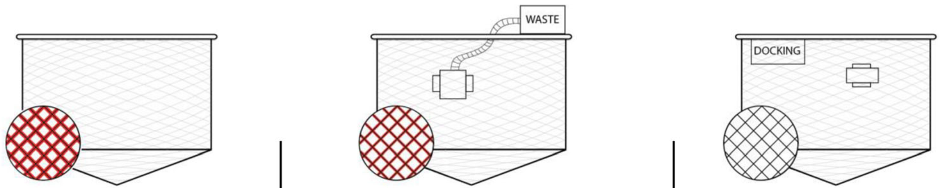
There is considerable variation in cost for net coating and cleaning depending on the location, size, environmental setting, farming strategy and other aspects of salmon farms. Following consultation with a range of aquaculture companies and aquaculture service providers operating in Norway, we estimate that, for an average production cycle (18 months), the average cost of antifouling coating treatment approximates US$ 30 200 per net pen (50 m diameter × 35 m deep, circular pen with conical bottom section; Supporting Information, Oppedal *et al.* 2011a). Individual net cleaning events cost approximately US $ 2100 per pen, and on average around 15 cleaning events are required per production cycle in regions with high biofouling pressure when using coated nets, increasing to 25 cleaning events when not using antifouling coatings. For a typical salmon farm with eight production pens, this amounts to a total production cycle cost of US$ 420 000 to $ 493 600 for biofouling management. All of these are direct costs for external services and exclude farm personnel costs (Table 1). According to one of Norway's largest salmon farming companies, biofouling prevention and removal approximates 2.2% of the production costs of individual sites. However, *indirect costs* related to biofouling (e.g. reduced biomass growth due to reduced appetite, increased mortality of cleaner fish and increased requirement for repairs of deployed nets) are not included and may exceed this estimate considerably.

Taking stock – how adequate are current practices?

The estimated combined total cost of traditional biofouling management of US$ 420 000–493 600 per farm per production cycle seems staggering given: (i) the short-lived protection current biofouling control technology provides and (ii) the associated impacts relating to antifouling and biofouling waste release (see sections above). The monetary extent of most of these impacts – in particular, those on salmon welfare, environmental integrity and public perception of the industry – has not been quantified. It is important that this is addressed, as it would enable the aquaculture industry and technology developers to appreciate the benefits that improvements in biofouling management technology could achieve, and the potential savings (cost reduction) – or even profit increases – that could be realised over time.

Cost-effective and environmentally sustainable biofouling management is an important objective for the salmon farming industry (Aquaculture Stewardship Council 2019; Grieg Seafood 2019; Mowi 2019), and its pursuit requires the development and implementation of an effective strategy. There are several alternative models for antifouling and biofouling management that could be pursued, and each would require dedicated investment, research and development into distinct (and different) areas of science and technology.

Here, we outline three strategies for management of biofouling that we consider are the most promising to support fish health and welfare while minimising impacts on the environment (Fig. 2). We then describe and project the potential savings (and profit) that the pursuit of improved



	Strategy 1 **Efficient antifouling coating**	Strategy 2 **Antifouling with intermittent cleaning**	Strategy 3 **Grooming of nets**
Functionality	Potent antifouling prevents biofouling over entire production cycle	Improved antifouling limits biofouling development, improved cleaning tools allow waste capture	Continuous cleaning prevents biofouling development
Advantages	• No cleaning-related costs • No cleaning-related impacts on fish health, coating, and environment	• Reduced cleaning-related costs • Reduced cleaning-related impacts on fish health, coating, and environment	• No cleaning-related impacts on fish health and environment
Challenges	• Efficacy across taxonomic spectrum • Environmental toxicity • Entanglement of drifting biomass	• Cleaning-related impacts • Environmental toxicity	• Energy efficiency • Tetherless, battery operated cleaning system with docking station
R&D needs	• Desired features of novel coatings/materials: - efficient - environmentally benign - good leaching control - highly robust	• Evaluation of potential materials (e.g., copper alloy mesh) and gentle cleaners • Cleaning waste collection	• Current available grooming technology needs evaluation • Desired features of novel cleaners: - autonomous - good cleaning efficiency - energy efficient - no impact on fish • Evaluate combination with foul-release coatings

Figure 2 Overview of the three suggested biofouling management strategies.

biofouling management may achieve, over and above initial investments required to change from the current status quo.

Strategies for future biofouling management

Strategy 1: efficient antifouling coating without cleaning

One option is to pursue the development and use of antifouling coatings or surface treatments that are effective for an entire production cycle and that do not require cleaning. This would necessitate the development of biocidal or surface-active coatings (or materials) that are more effective than today's options but that, in the absence of cleaning, are environmentally benign or within acceptable ecotoxic and contaminant limits. By preventing the accumulation of biofouling altogether, none of the issues related to biofouling presence or removal (see above) would be relevant. Thus, such a coating would save considerable amounts of money currently spent on net cleaning and reduce risks related to health, welfare or survival caused by today's practices.

The development of a coating or material that is effective against all biofouling organisms for an entire production cycle will have to face two main obstacles. First, biofouling communities are often highly variable, consisting of organisms from almost all species classes (Fitridge *et al.* 2012; Bloecher *et al.* 2013; Bannister *et al.* 2019). Their sensitivity and tolerance towards biocides are equally diverse, resulting in the repellence of many but rarely all organisms by one product (Hall 1980; Perrett *et al.* 2006; Chambers *et al.* 2012; Edwards *et al.* 2014). The remaining low-diversity assemblages of resistant organisms are often highly successful colonisers and are still able to achieve high abundance (Guenther *et al.* 2010). Second, if a biocide is efficient against a broad range of fouling organisms, it frequently also affects non-target organisms. Unless minimal leaching or loss to the environment can be achieved, potent biocides are likely to be unacceptable for widespread use in coastal areas – tributyl tin (TBT) being a prime example (Guardiola *et al*. 2012; Amara *et al*. 2018).

Even if an effective antifouling coating/material can be developed, a final – if not necessary frequent – challenge for the use of an 'antifouling only' strategy remains: drifting (and often dead) algal material such as kelps and conglomerates of filamentous algae is passively transported by currents, sometimes in considerable quantities, and can become entangled in pen nets (Bloecher & Floerl 2020). This can cause occlusion-related impacts on the cage environment, as described in earlier sections and may thus require removal.

Implementability

While some commercially available antifouling coatings are suitable for preventing biofouling for extended periods of time in regions with very low biofouling pressure, there are (to our knowledge) no coatings or materials currently on the market that can protect nets for prolonged periods in biofouling-prone regions. The most potent biocides in use today are based on copper, whose environmental impacts have received considerable attention (Burridge *et al*. 2010; Guardiola *et al*. 2012; Amara *et al*. 2018). However, due to global demand across maritime industries beyond aquaculture, international companies and research institutes are heavily involved in the development of novel antifouling solutions. One recent example is the development of 'non-biocide-release' coatings where the novel, metal-free biocide Econea is immobilised in foul-release coatings using covalent bonds. During trials in temperate and tropical environments, long-lasting protection (>2 years) was achieved, with no or minimal associated release of biocide (Silva *et al*. 2019; Ferreira *et al*. 2020). While Econea-based coatings designed for finfish aquaculture do not yet show the same long-lasting performance (Bloecher & Floerl 2020), the antifouling system innovations around Econea illustrate the potential of novel antifouling approaches. To implement Strategy 1, research and development should focus on the development of novel antifouling coatings, surfaces or materials with high efficacy (full grow-out cycle) that are based on an environmentally benign biocide/s or whose leaching rates are within acceptable environmental limits, while being robust against wear and degradation.

Strategy 2: antifouling combined with intermittent cleaning

This strategy avoids the need to prevent biofouling development for the entire duration of the grow-out phase. In this case, the antifouling coating (or material/surface) should be able to prevent the settlement of antifouling-sensitive organisms and delay and reduce settlement and growth of the more resistant ones. This would considerably reduce the need for net cleaning, thereby also reducing the associated risks to fish health and the environment.

Antifouling coatings need to be based on environmentally benign biocides, and leaching rates need to be within environmentally acceptable limits. In order to allow cleaning once biofouling has accumulated, the coating/material needs to be structurally robust to withstand multiple net cleaning events during a grow-out phase without incurring damage that leads to performance reduction or increased release of biocides or other contaminants (Bloecher *et al*. 2019). This would have the added advantage that re-coating or recycling of the remaining coating or net material at the end of the season would allow to further reduce costs and environmental impacts. Ideally, net cleaning should include the collection of the biofouling particles removed from the net. This will prevent contact with the fish and subsequent irritation of gills and other sensitive tissues, or transmission of diseases to the fish or adjacent farms. It will also limit the release of coating particles into the environment.

Implementability

As there are no non-biocidal coatings commercially available at the moment that offer sufficient biofouling protection, implementation of this strategy would currently need to rely on a biocidal coating or material. A potential candidate for this strategy is copper alloy metal netting due to its superior antifouling ability (Chambers *et al*. 2012; Drach *et al*. 2013). However, as the initial leaching rate may be higher compared to conventional net coatings (Drach *et al*. 2013; Kalantzi *et al*. 2016), more data are needed to evaluate the ecological impacts in relation to a prospective long-term use. In this context, an analysis of net stability over time is essential to determine the operational capability for copper alloy metal nets for long-term use, in addition to a cost–benefit analysis to identify feasibility for farmers.

Systems based on low-pressure/high water volume or cavitation are promising candidates for low-impact cleaning, required, for example, by accreditations such as the ASC Standard (Aquaculture Stewardship Council 2019; Bloecher *et al*. 2019). While the former is commercially available and in use today, cavitation-based systems are not yet widely available, and an independent evaluation of both commercial systems is currently lacking. Such an evaluation would also indicate aspects of the technology that may benefit from improvement.

To implement Strategy 2, research and development should focus on the development of efficient and mechanically resistant antifouling net materials, surfaces or coatings and the development of pen cleaning technology that does not impact on net/surface/coating integrity and is able to collect and contain cleaning waste. Here, the cooperation between antifouling and cleaning technology manufacturers to facilitate the development of the most efficient and robust combinations is of paramount importance. In recent years, some countries (e.g. New Zealand, Australia and the United States) have developed performance standards for in-water cleaning operations of ocean-going vessels. This has led to the formation of research and development partnerships involving cleaning and antifouling technology developers, scientists and government agencies, and a series of promising international projects to enable the development of fit-for-purpose technologies (Scianni & Georgiades 2019; Tamburri 2019). Such initiates could also help the development of novel approaches to aquaculture biofouling management. To evaluate the suitability of copper alloy metal nets for this strategy, their feasibility for and functionality under long-term use as well as their environmental impacts need further assessment. Finally, the investigation of potential uses of collected biofouling organisms (fertiliser, biofuel, bioactives etc.) may further incentivise the development of novel aquaculture cleaning waste collection technologies.

Strategy 3: grooming of nets without antifouling

This strategy is based on a net that can be cleaned at high frequency ('groomed') to prevent the maturation of the biofouling community and minimise the amount of material removed and released, including materials that may be harmful to the fish (e.g. nematocyst-bearing organisms). Since the growth of biofouling is ideally disturbed during or soon after settlement and before secure attachment of organisms has occurred, removal will be easier than that of mature communities. Removing organisms before they reach maturity will also avoid the release of propagules and reproductive stages during net cleaning which otherwise would support increased re-colonisation and local spread of biofouling species (Carl *et al.* 2011). Capture of cleaning waste would not be required due to an absence of antifouling material and minimal fouling biomass. The effective grooming frequency will depend on biofouling pressure and growth rates of key organisms and thus vary with region and season. Regular prophylactic grooming combined with the use of abrasion-resistant non-biocidal coatings is also being explored or applied in parts of the global shipping industry (Tribou & Swain 2017; Hunsucker *et al.* 2019).

While uncoated nets can be utilised for this strategy, the addition of a non-biocidal coating may help to protect the net from UV radiation damage and abrasion by frequent cleaning. The use of such coatings serves to seal the surface of the net, resulting in reduced surface roughness and, potentially, colonisation rates (Baum *et al.* 2017). Reduced surface roughness can also help to improve removal of biofouling organisms (Hodson *et al.* 2000; Swain & Shinjo 2014). By using such surfaces, more gentle net cleaning technology can be used, further protecting the coating from abrasion and facilitating longevity. The cleaning units employed for grooming should operate as autonomously as possible to minimise labour costs and allow operation independent of work schedules and weather conditions and in remote locations. Current development of net grooming technology is aimed at small, autonomous units that would be assigned to a single or a small number of pens. Ideally, these units should be battery-operated and tetherless to avoid entanglement with other equipment in the pen. While in principle the cleaning mechanisms for grooming may not fundamentally differ from 'regular' net cleaning technology, the prospects of battery-operated autonomous units encourage new developments.

Implementability

Currently, this strategy can be implemented using uncoated nets or nets with available non-biocidal wax- or resin-based coatings that increase robustness of the net and potentially make removal of biofouling easier. Recently, silicone-based foul-release coatings were tested with regard to use on aquaculture nets. While they improve biofouling removal, they are currently not robust enough to be used in a commercial setting (Hodson *et al.* 2000; Swain & Shinjo 2014). Instead of coatings, nets made from materials other than nylon (e.g. high density polyethylene (HDPE) or polyethylene terephthalate (PET) monofilament) are available that feature a smooth surface structure and that have the potential to delay the onset of biofouling and ease cleaning (Edwards *et al.* 2014). However, the development of appropriate net grooming technology is still in its infancy and it is uncertain whether the semi-autonomous, brush-based cleaning units currently on the market are capable of undertaking regular grooming with high efficacy.

To implement Strategy 3, research and development should focus on: (i) the development of net cleaning technology that operates autonomously, has high cleaning efficacy, is energy-efficient, has no mechanical impact on nets/coatings and does not impact on fish within cleaned pens; and (ii) the development or refinement of novel net materials and/or coatings that protect nets from abrasion, UV radiation and that improve removal of biofouling.

The choice of strategy and the need for rigorous cost–benefit analyses

The choice of strategy for any salmon farming company depends on many factors, with local biofouling pressures, cost-efficiency and compliance with accreditation schemes (e.g. the ASC Salmon Standard) being the most influential ones. At present, none of the three strategies can be readily applied without limitations – Strategy 1 being particularly beyond current reach – due to a lack of proven and readily available technologies. However, the pursuit of either strategy can commence immediately based on the research and development priorities set out above. In combination with adequate record-keeping and documentation of cost, performance and limitations of existing and developing mitigation tools, critical knowledge gaps can be filled and facilitate progress towards each strategy's objective. Documented successes with regard to cleaning efficacy, fish health and welfare, energy consumption and environmental impacts will further boost motivation and support and enable farming companies to make informed strategic choices for their sites.

During our decade-long interactions with the aquaculture farming and the supporting technology industries, we have repeatedly come across scepticism from both industries regarding the development and validation of improved biofouling management systems. Farmers are frequently worried about departing from current practices because: (i) this is associated with new costs and uncertainty, (ii) *demonstrably* improved technology is currently unavailable, and (iii) there are substantial financial risks involved if 'the new thing' fails. Technology developers and manufacturers, on the other hand, are uncertain about sufficient and sustained demand for new biofouling management tools and the profitability of investments required for their development. Both parties' concerns are understandable and, we think, caused by the absence of resolved cost–benefit relationships, that is an understanding of the benefits that could be achieved by improving the effectiveness and reducing the impacts of biofouling management, and how these benefits compare in the short-, medium- and long-term against the costs of developing and implementing new technologies required to realise them. Over the past decades, the global maritime shipping industry has managed to vastly improve vessels' level of protection from biofouling via continued and significant investments in new technology development. This was helped by an understanding of the immense costs associated with inadequate biofouling protection (increased fuel costs, greenhouse gas emissions, reduced speed and resulting opportunity costs, etc.) (Davidson *et al.* 2016; Fernandes *et al.* 2016). Given the projected growth and global importance of sea-based fish farming, the international aquaculture industry has a similar opportunity.

The conceptual diagram in Figure 3 illustrates how investments into improved biofouling management – via Strategies 1, 2 or 3 – could lead to long-term savings in salmon aquaculture. The progression from 'Status quo' to an 'Established strategy', with its associated reductions in impacts, represents a conceivable development over time. The pursuit of new strategies for biofouling management will likely lead to a first 'Transitional phase' (Fig. 3). In this phase, the direct cost of biofouling management is likely to increase as investments in research and development and potentially significant operational changes are required. We consider that already in this first phase a modest reduction in the impacts of biofouling on salmon production, operations and environment can be achieved because a considerable part of current impacts is caused by current approaches to antifouling and net cleaning (Floerl *et al.* 2016; Bannister *et al.* 2019; Bloecher *et al.* 2019). This may result in the overall monetary costs associated with biofouling (management + impacts) exceeding the status quo due to increased direct costs. However, reduced impacts on environment and welfare might also trigger other indirect benefits such as reduced public resistance to future aquaculture development (increased social licence to operate) and improved product image or demand (Quigley & Baines 2014; Froehlich *et al.* 2017). Neither of these have yet been quantified, but their monetary-equivalent value may be considerable.

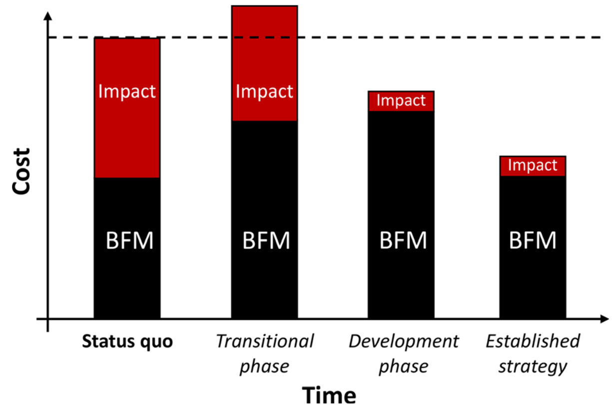


Figure 3 Illustrated process of implementing novel biofouling management strategies 1–3, showing how investment into research and development can decrease the overall costs salmon farming incurs from biofouling. Black bars indicate direct costs associated with current biofouling management (BFM) practices including investment into improved (more cost-effective) biofouling management. Red bars indicate indirect costs including impacts of biofouling (and current management approaches) on fish health and welfare, environmental pollution, equipment wear and restrictions with regard to, for example accreditation schemes. Costs and differences between bars are conceptual and for illustration.

As the technologies and their operational implementation progress, biofouling management costs may increase further as tools and approaches are being refined (Fig. 3; Development phase). However, we predict that this will be accompanied by a more substantial reduction in the impacts of biofouling on salmon production, operations and environment. As a net outcome, total monetary costs may be reduced relative to the status quo, despite increased biofouling management expenditure, resulting in net savings. In addition to these, reduced impacts on environment and welfare might bear unknown benefits such as those described above.

Depending on the scale of uptake of improved biofouling management strategies across the industry, direct costs of biofouling management may decrease further as technology becomes more affordable and operational teams and protocols more experienced and efficient. The combination of increased cost-effectiveness of biofouling management and the associated decrease in biofouling related impacts may result in a further reduction in the total cost of biofouling to the industry (Fig. 3; Established strategy).

The phases and developments described in Figure 3 represent a conceptual view based on experience and familiarity with biofouling management in salmon aquaculture. It is not possible to predict the timeframe or the exact magnitude of overall improvements and savings associated with the pursuit of new strategic approaches as these are dependent on technology performance, industry uptake, regional biofouling pressures, government regulations or interventions, and salmon aquaculture market development. However, the development of economic net benefit over time proposed in our conceptual model (Fig. 3) is consistent with evidence-based analysis of the benefits of invasive species management. Hanley and Roberts (2019) demonstrate that dedicated efforts into the management of unwanted invasive species (analogous to biofouling in this paper) will be associated with high short-term costs, but followed by significant long-term cumulative benefits. Figure 4 represents an adaptation of Hanley and Roberts' (2019) economic model to biofouling management in marine aquaculture and illustrates the development of cumulative net benefit over time, following a period of increased costs (analogous to Transitional phase in Fig. 3). The economic theories described by Hanley and Roberts (2019) and Figure 4 are also confirmed by real-world examples from terrestrial farming systems, where the development and implementation of novel 'Precision Agriculture Technologies' – associated with substantial costs – have over time achieved significant reductions in greenhouse gas emissions, fertiliser and water usage, while increasing farm productivity (Balafoutis *et al*. 2017).

The average mortality of salmon during the grow-out phase at sea is 14–16% (Sommerset *et al*. 2020), with maximum mortalities at the beginning and at the end of the production cycle (Salama & Murray 2011; Bang Jensen *et al*. 2020). While there are no reliable data on the exact contribution of biofouling- or biofouling management-related impacts to farm mortality, we consider, based on recent assessments (Bannister *et al*. 2019), that improved biofouling management has the potential to significantly improve fish health and welfare, and thereby survival. Using industry data (Mowi 2019) on the impacts of farmed salmon mortality on profit, we derived that each 1% increase in survival associated with a single production cycle on a typical salmon farm (producing 6480 tons of salmon) would result in a 3% (~US$ 0.4 M) increase in profit (Supporting Information). At the scale of the Norwegian and Scottish salmon farming industry (1.4 M tonnes annual production; Marine Scotland Science 2019; Norwegian Directorate of Fisheries 2020), increased survival of 1% or 2% would increase industry-wide profit by US$ 85.5 and US$ 171 million, respectively, not including associated indirect benefits arising from increased social licence. Although admittedly simplified, the scale of potential net gains over time is significant. This provides a strong incentive for strategic rethinking and investment – the examples from terrestrial agriculture and invasive species management discussed above provide tangible evidence that net benefits are achievable.

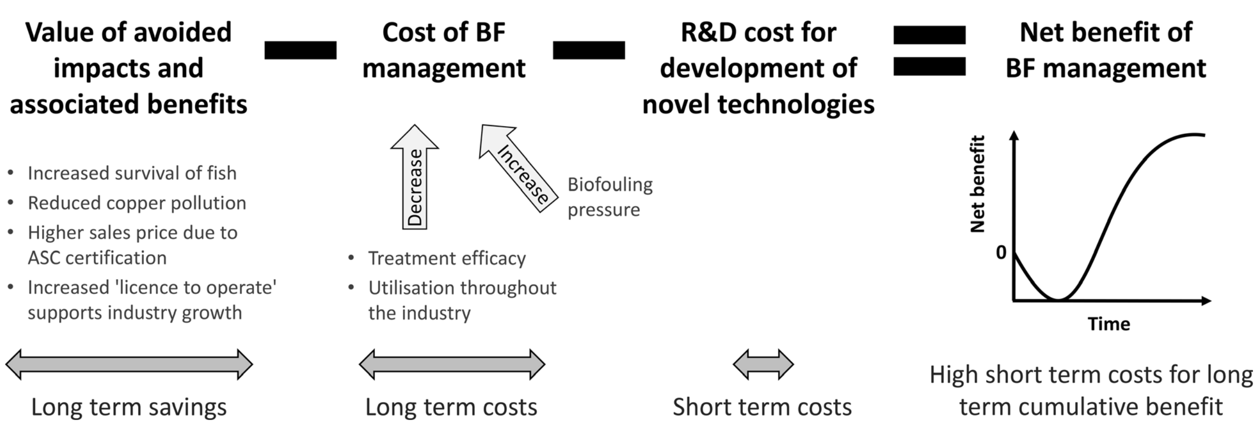


Figure 4 Calculation of the net benefit of biofouling (BF) management, adapted from Hanley and Roberts (2019).

Recommendations and conclusions

Biofouling has been an issue since humans started to immerse mobile and static infrastructure in the marine environment (Redfield *et al*. 1952), and it is unlikely to ever be fully overcome. Even if the use of cleaner fish in Norwegian salmon aquaculture may decline, and thereby the greatest current driver for net cleaning, the need for biofouling management and minimisation will persist to mitigate other threats, such as the increasing risks of aquaculture disease pathogens associated with biofouling (e.g. vibriosis; Pietrak *et al*. 2012; Albert & Ransangan 2013) or damage caused by the exposure of fish tissues to biofouling (e.g. gill and skin damage by cnidarians; Baxter *et al*. 2012; Fisher & Appleby 2017; Bloecher *et al*. 2018).

A multitude of tools and approaches – at various stages of development – are available for biofouling control in salmon aquaculture. Given the variation in farming environments, a single 'silver bullet' has so far not been developed and may never be. To ensure cost-effective use of resources, clear objectives need to be set for biofouling management, and strategies adopted for achieving them in the context of local or regional conditions. This will require investments into the development and evaluation of fit-for-purpose technologies that will achieve far-reaching benefits over appropriate time scales. The greatest rate of progress and benefit is likely to be achieved via multi-disciplinary and industry-wide collaborations, and even sharing of research and development results among the industry for the greater good.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supinfo. Data input for the calculation of the costs of biofouling management.