Biofouling
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The impact and control of biofouling in marine aquaculture: a review

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Biofouling in marine aquaculture is a specific problem where both the target culture species and/or infrastructure are exposed to a diverse array of fouling organisms, with significant production impacts. In shellfish aquaculture the key impact is the direct fouling of stock causing physical damage, mechanical interference, biological competition and environmental modification, while infrastructure is also impacted. In contrast, the key impact in finfish aquaculture is the fouling of infrastructure which restricts water exchange, increases disease risk and causes deformation of cages and structures. Consequently, the economic costs associated with biofouling control are substantial. Conservative estimates are consistently between 5–10% of production costs (equivalent to US$ 1.5 to 3 billion yr^{-1}), illustrating the need for effective mitigation methods and technologies. The control of biofouling in aquaculture is achieved through the avoidance of natural recruitment, physical removal and the use of antifoulants. However, the continued rise and expansion of the aquaculture industry and the increasingly stringent legislation for biocides in food production necessitates the development of innovative antifouling strategies. These must meet environmental, societal, and economic benchmarks while effectively preventing the settlement and growth of resilient multi-species consortia of biofouling organisms.

Keywords: aquaculture; antifouling; fish; shellfish; fouling; net; sea-cage

Introduction

Aquaculture is a globally important industry providing essential food to a growing world population, with a critical role in the supply of protein to low income, food deficient countries. In 2009, aquaculture provided more than half of the fish consumed by humans, exceeding 55.7 million tonnes and a value of US$ 105 billion (FAO 2010). Of the total economic value of aquaculture, marine shellfish and marine finfish represent over US$ 31.4 billion (30%; FAO 2010) and these commercially cultivated species are either high value, or can be cultured intensively to ensure large biomass production. Commonly cultivated marine shellfish are oysters (*Crassostrea* spp., *Ostrea* spp.), mussels (*Mytilus* spp., *Perna* spp.) and scallops (*Placopecten* spp., *Chlamys* spp.), while the principal species reared in marine fish culture are salmonids (*Salmo salar*, *Oncorhynchus* spp.), mullets (*Mugil* spp., *Chanos chanos*), kingfish (*Seriola* spp.), tunas (*Thunnus* spp.), sea breams (*Sparus* spp., *Pagrus* spp.) and sea basses (*Dicentrarchus labrax*, *Lates* spp., *Lateolabrax japonicus*).

The production infrastructure for these species invariably consists of a complex assortment of submerged components with cages, nets, floats and ropes. All of these structures serve as surfaces for biofouling. Shells in shellfish culture also provide an ideal and accessible biofouling surface. The presence of such large and varied surfaces provides for a broad diversity of epibiotic organisms to settle and grow. These marine algae and animals, collectively termed biofouling, are severely problematic to culture operations and can have significant economic impacts.

The direct economic costs of biofouling control to the aquaculture industry are substantial, with conservative estimates of 5–10% of production costs attributed to biofouling (Lane and Willemsen 2004). Globally, this equates to costs of US$ 1.5 to 3 billion yr^{-1}. While the direct costs of biofouling control have been estimated for many aquaculture species (salmon: US$ 0.03 and $ 0.12 per kg of salmon produced; Olafsen 2006; scallops: 30% of final market price; Claereboudt et al. 1994; oysters: 20% of final market price; Enright 1993; Watson et al. 2009), the indirect effects of fouling on the production of cultured species remain largely unassessed. The production chain inefficiencies associated with biofouling are substantial,

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Table 1. An overview of common fouling organisms in marine shellfish culture and their documented adverse impacts.

Fouling organism	Range of known impacts	Region	Shellfish species affected	Author(s)
Chordata: Ascidiacea				
Botryllus schlosseri *Ciona intestinalis* *Dicarpa* sp. *Didemnum perlucidum* *Didemnum* sp. *Didemnum vexillum* *Diplosoma* sp. *Styela clava* *Styela plicata*	Physical disruption to opening and closing of valves Reduced size and/or condition Mortality Competition for food Stock losses	Australia Brazil Canada China Japan Netherlands New Zealand Norway Persian Gulf	*Mytilus edulis* *Perna canaliculus* *Perna perna* *Pinctada radiata (=fucata)* *Pinctada maxima* *Pinctada martensi (=fucata)* *Pinctada fucata*	Takemura and Okutani (1955); Miyauti (1968); Alagarswami and Chellam (1976); Mohammad (1976); Dharmaraj et al. (1987); Chengxing (1990); Doroudi (1996); Carver et al. (2003); Coutts and Sinner (2004); Bourque et al. (2005); Guenther et al. (2006); Mallet and Carver (2006); Forrest et al. (2007); LeBlanc et al. (2007); Locke et al. (2007); Bonardelli (2008); Denny (2008); Ramsay et al. (2008); Daigle and Herbinger (2009); Gittenberger (2009); Rocha et al. (2009); Paetzold and Davidson (2010); Comeau et al. (2012)
Turbellaria: Polycladida				
Imogine mcgrathi *Stylochus* sp. *Stylochus matatsai* *Stylochus frontalis*	Mortality	Australia Mexico	*Crassostrea rhizophorae* *Mytilus galloprovincialis* *Pinctada margaritifera* *Pinctata mazatlantica*	Littlewood and Marsbe (1990); Newman et al. (1993); Monteforte and Garcia-Gasca (1994); Pit and Southgate (2003)
Annelida: Polychaeta				
Boccardia knoxi *Hydroides elegans* *Polydora hoplura* *Polydora websteri* *Polydora ciliata* *Polydora vulgaris* *Pomatoceros triqueter*	Blisters in nacreous layer Weakened shell Devaluation Mortality	Arabian Gulf Australia Indian Ocean Japan Red Sea UK USA	*Haliotis* spp. *Mytilus edulis* *Pinctada fucata* *Pinctada margaritifera*	Crossland (1957); Mohammad (1972); Blake and Evans (1973); Alagarswami and Chellam (1976); Mohammad (1976); Dharmaraj and Chellam (1983); Velayudhan (1983); Dharmaraj et al. (1987); Arakawa (1990); Wada (1991); Doroudi (1996); Taylor et al. (1997); Campbell and Kelly (2002); Lleonart et al. (2003)
Algae				
Cladophora sp. *Codium fragile* spp. fragile *Cyanobacteria* *Undaria pinnatifida*	Shell erosion Lost stock Overgrowth Smothering	Canada New Zealand	*Mytilus edulis* *Perna canaliculus* *Pinctada margaritifera*	Mao Che et al. (1996); Garbary and Jess (2000); Naylor et al. (2001); Provan et al. (2005); Forrest and Blakemore (2006); Sharp et al. (2006); Wells et al. (2009)
Porifera				
Callyspongia fibrosa *Cliona celata* *Cliona dissimilis* *Cliona margaritiferae* *Cliona orientalis* *Cliona* sp. *Cliona vastifica* *Pione velans*	Brittleness Hinge instability Blister formation Shell damage Shell deformity Mortality	Australia French Polynesia Indian Ocean Persian Gulf Red Sea	*Chlamys islandica* *Ostrea edulis* *Pinctada fucata* *Pinctada margaritifera* *Pinctada margaritifera* var. *cumingii* *Pinctada radiate* *Placopecten magellanicus*	Korringa (1952); Crossland (1957); Evans (1969); Mohammad (1972); Algarswami and Chellam (1976); Mohammad (1976); Thomas (1979); Dharmaraj and Chellam (1983); Velayudhan (1983); Dharmaraj et al. (1987); Pomponi and Meritt (1990); Barthel et al. (1994); Doroudi (1996); Mao Che et al. (1996); Wesche et al. (1997); Moase et al. (1999); Rosell et al. (1999); Fromont et al. (2005)
Mollusca: Bivalvia				
Crassostrea sp. *Lithophaga* sp. *Martesia* sp. *Mytilus* sp. *Pinctada* sp. *Pinna* sp. *Pteria* sp. *Saccostrea* sp.	Physical disruption to opening and closing of valves Damage to shell Recession of shell growth Shell deformity Mortality Competition for food and space	Australia India Indonesia Persian Gulf Red Sea	*Pinctada fucata* *Pinctada margaritifera* *Pinctada maxima* *Pinctada radiata*	Takemura and Okutani (1955); Crossland (1957); Alagarswarmi and Chellam (1976); Dharmaraj et al. (1987); Doroudi (1996); Taylor et al. (1997); Guenther et al. (2006)
Cnidaria: Hydrozoa				
Amphisbetia bispinosa *Ectopleura crocea* *Ectopleura larynx*	Smothering Recession of shell growth	Australia Canada Japan	*Adamussium colbecki* *Mizuhopecten yessoensis*	Claereboudt et al. (1994); Cerrano et al. (2001); Heasman and de Zwart (2004); Getchis (2006); Guenther and de Nys

(*continued*)

Table 1. (*Continued*).

Fouling organism	Range of known impacts	Region	Shellfish species affected	Author(s)
Eutima japonica *Hydractinia angusta* *Obelia bidentata* *Tubularia* sp.	Devaluation Competition for food and space Stress Disruption to feeding Physical disruption to opening and closing of valves Facilitate settlement of other foulers Deter shellfish recruitment	New Zealand USA	*Mytilus edulis* *Mytilus galloprovincialis* *Perna canaliculus* *Placopecten magellanicus*	(2006); Baba et al. (2007); Fitridge (2011)
Arthropoda: Maxillopoda				
Balanus amphitrite communis *Balanus amphitrite variegates*	Physical disruption to opening and closing of valves Recession of shell growth Mortality	Arabian Gulf Australia India Indonesia Japan Persian Gulf	*Pinctada fucata* *Pinctada martensi* *Pinctada maxima* *Pinctada radiata*	Takemura and Okutani (1955); Miyauti (1968); Alagarswarmi and Chellam (1976); Mohammad (1976); Dharmaraj and Chellam (1983); Dharmaraj et al. (1987); Wada (1991); Doroudi (1996); Taylor et al. (1997); de Nys and Ison (2004)

and the overall impact and cost of biofouling in marine aquaculture is significantly underestimated.

To minimise these impacts, the aquaculture industry uses technologies and husbandry techniques to manage and control fouling communities. The composition of fouling communities and their effect in marine aquaculture is largely dictated by the properties of the fouling surface, and the protection and management of these surfaces is the key to biofouling control. In the shellfish industry the control of biofouling is centred around maintaining clean shells, as biofoulers have detrimental effects on the appearance and marketability and on the growth and condition of shellfish. While fouling organisms settle onto infrastructure such as ropes and floats causing breakages and costly repairs, their attachment to the surfaces of cultured shells is more problematic. In contrast, in the marine finfish industry cage nets and supporting infrastructure offer fouling organisms thousands of square meters of multifilament netting. The primary focus in fish culture therefore relates to the mitigation of net fouling, as this leads to compromised cage structure (Swift et al. 2006) and detrimental effects on fish health mainly through low flow-through of water, leading to poor dissolved oxygen availability. Consequently, the control of biofouling is a specific and complex problem within each industry sector, where the prevention and/or removal of fouling organisms requires the development of technologies and application methods to minimise the impacts on non-target organisms and the culture environment.

This review discusses the impact of biofouling on aquaculture species and operations across the entire production chain, and critically assesses the effectiveness of methods currently in use, and in development, for the control of biofouling. The focus is specifically on marine shellfish and finfish as biofouling is ubiquitous and problematic in these production systems. As biofouling has fundamentally different effects in the shellfish and finfish production systems, these are separated throughout the review. Furthermore, rather than reporting a compendium of studies on marine biofouling, a comprehensive list of common fouling organisms and their impacts in aquaculture are provided in Table 1 for shellfish and in Table 2 for finfish.

Fouling communities in aquaculture

Biofouling on marine surfaces, including those provided by aquaculture structures and stationary stock, develops through a well known ecological process (reviewed in Maki and Mitchell 2002), whereby macrofouling derived from the spores and propagules of algae, and the larvae of invertebrates such as hydroids, ascidians, sponges, bryozoans, barnacles, bivalves and polychaetes, develops rapidly within days to weeks.

All biofouling communities vary temporally and spatially. Major temporal changes are driven by seasonality in marine invertebrate populations. The arrival of new recruits, periods of intense growth, or times of dormancy and regression, all impact on community development at different times of the year. Spatial variability in marine invertebrate

Table 2. An overview of common fouling organisms in marine finfish culture and their documented adverse impacts.

Fouling organism	Range of known impacts	Region	Fish species affected	Author(s)
Chordata: Ascidiacea				
Ascidiella aspersa *Botrylloides* sp. *Botryllus schlosseri* *Styela plicata* *Symplegma* sp. *Trididemnum* sp.	Cage deformation and structural fatigue Increased disease risk	Malaysia UK	*Epinephelus* sp. *Lates calcarifer* *Lutjanus* sp. *Salmo salar* *Siganus* sp.	Milne (1975b); Tan et al. (2002); Braithwaite et al. (2007)
Algae				
Antithamnion sp. *Ectocarpus* spp. *Enteromorpha* spp. Filamentous diatoms *Gracilaria* sp. *Ulva* spp.	Net occlusion Restriction of water exchange Poor water quality Limited oxygen availability Reduced waste metabolite removal Cage deformation and structural fatigue	Australia UK USA Malaysia	Epinephelus sp *Lates calcarifer* Lutjanus sp. *Oncorhynchus tshawytscha* *Salmo salar* *Siganus* sp. *Thunnus maccoyii*	Milne (1975a); Milne (1975b); Moring and Moring (1975); Hodson and Burke (1994); Cronin et al. (1999); Svane et al. (2006)
Mollusca: Bivalvia				
Crassostrea spp. *Electroma georgiana* *Modiolus* sp. *Mytilus edulis* *Perna viridis* *Pinctada* spp.	Net occlusion Cage deformation and structural fatigue	Australia Malaysia Singapore UK USA	*Epinephelus* sp *Lates calcarifer* *Lutjanus* sp. *Oncorhynchus tshawytscha* *Salmo salar* *Siganus* sp. *Thunnus maccoyii*	Milne (1975a); Milne (1975b); Moring and Moring (1975); Lee et al. (1985); Cronin et al. (1999); Braithwaite et al. (2007); Greene and Grizzle (2007)
Cnidaria;: Hydrozoa				
Ectopleura larynx *Obelia dichotoma* *Plumularia* sp. *Tubularia* sp.	Net occlusion Reduced water flow	Malaysia Norway USA	*Lates calcarifer* *Salmo salar*	Hodson et al. (2000); Guenther et al. (2009); Madin et al. (2009); Guenther et al. (2010); Carl et al. (2011); Guenther et al. (2011)

communities varies on both the small and large scale (Fraschetti et al. 2005) and between temperate and tropical waters. Variation is primarily driven by planktonic events, larval choices during attachment and settlement, and metamorphosis and mortality (Holloway and Keough 2002a, 2002b) that also correlate with differences in environmental conditions. For example, a diverse range of algae and marine invertebrates occur on fish cages in marine waters compared to the algal monocultures in brackish waters (Santhanam et al. 1983). In contrast, variation in biofouling within sites is predominantly driven by the availability of light and water flow and is often related to the depth and orientation of infrastructure (eg Cronin et al. 1999; Howes et al. 2007; Guenther et al. 2010). Fouling communities generally decrease in biomass and become less diverse in deeper waters (Cronin et al. 1999; Guenther et al. 2010).

Common fouling organisms in aquaculture settings

Although spatial and temporal differences exist in the overall composition and biomass of fouling communities, in general, a common suite of sessile, suspension-feeding organisms dominate. These include diverse organisms including barnacles, bivalves, bryozoans, polychaetes, ascidians, hydroids, sponges and algae (Figure 1, Tables 1 and 2). A commonly occurring trait across most of these taxa is their 'invasiveness'. Many are cosmopolitan in their distribution, being frequently transferred around the globe by shipping, and possess an ability to survive and reproduce in a new location. An example of 'invasiveness' is the vase tunicate *Ciona intestinalis* (Figure 1a), now one of the most problematic fouling organisms in global mussel culture, particularly in north America (Edwards and Leung 2009). Although its native range is ambiguous due to its unresolved taxonomic status (Zhan et al. 2010), *C. intestinalis* has spread to aquaculture industries in temperate and tropical regions worldwide. It was first documented on the west coast of North America in the 1930s (Blum et al. 2007), and invaded the east coast of North America in 2004 (Ramsay et al. 2008). New populations have appeared over the past 50 years along the coastline of Australia, New Zealand, Asia, South Africa and South America (Therriault and Herborg 2008; Zhan et al. 2010). Given the ongoing change in global climate and factors that have facilitated the spread of *C. intestinalis* and other invasive biofouling

Figure 1. Common fouling organisms associated with aquaculture operations: (A) *Ciona intestinalis* (vase tunicate); (B) *Ectopleura crocea* (pink mouthed hydroid); (C) *Mytilus edulis* (blue mussel); (D) *Ectopleura larynx* (ringed tubularia).

organisms, there are compelling predictions for an increase in their spread (Stachowicz et al. 2002; Floerl et al. 2009; Sorte et al. 2010).

The impact of biofouling on aquaculture

While fouling community structure is spatially and temporally variable, the impact of fouling is, in nearly all cases, highly detrimental to aquaculture. Surprisingly, however, there are circumstances where biofouling is beneficial, or at least, does not affect production. For example, fouling can enhance shellfish growth (Dalby and Young 1993), increase primary production of phytoplankton and therefore food availability to shellfish (Lodeiros et al. 2002; Ross et al. 2002; Le Blanc et al. 2003), provide shellfish with protection against predation (Wahl et al. 1997; Manning and Lindquist 2003), facilitate the settlement of commercially farmed shellfish (Hickman and Sause 1984; Fitridge 2011) or mitigate disease risk (Paclibare et al. 1994). These examples, however, are the exception, and biofouling is primarily deleterious to the cost effective production of shellfish and fish.

Shellfish

The effects of biofouling of shell surfaces and equipment fall into five major categories: (1) physical damage by invasive organisms that bore into the shell (endoliths) or epibiotic calcareous organisms growing on the shell surface, affecting aesthetics; (2) mechanical interference of shell function due to colonisation of shells, particularly around the hinge and lip, affecting feeding ability and susceptibility to predators; (3) biological competition for resources such as food and space, affecting growth and condition; (4) environmental modification due to colonisation of culture infrastructure, leading to reduced water flow, waste build-up, decreased oxygen levels and reduced food availability. In addition, biodeposition and the spread of non-indigenous organisms can have deleterious effects on surrounding natural ecosystems; (5) increased weight from biofouling biomass on stock and equipment (eg panels, nets, ropes and floats), leading to greater production costs associated with extra maintenance requirements and loss of stock and equipment.

Physical damage

Physical shell damage occurs through the burrowing activities of endolithic organisms or from epibiotic calcareous tube dwelling polychaetes attached to the shell surface. Polychaete worms such as members of the genera *Polydora* and *Boccardia* penetrate and excavate shells, causing cavities, burrows, blisters and tunnels deep within the nacreous layer (Lleonart et al. 2003; Silina 2006; Simon et al. 2006). The effects are very destructive (Kaehler 1999), with hinge instability, disruption of shell formation, fragility, brittleness and loss of thickness (Mao Che et al. 1996). The shell becomes substantially weakened and vulnerable to predators and parasites (Kaehler and McQuaid 1999; Stefaniak et al. 2005; Buschbaum et al. 2007; Thieltges and Buschbaum 2007). An increased investment in energy expensive processes such as shell formation and regeneration ensues, causing reduced growth and reproductive output (Kaehler and McQuaid 1999; Stefaniak et al. 2005), a reduction in yield and quality and in extreme cases, mortality. Although less destructive to the structural integrity of the shell, tube dwelling polychaetes such as *Pomatoceros triqueter* and *Hydroides elegans*, are also damaging to shellfish culture. Fouled shellfish are considered visually unattractive and unappetising to consumers and are subsequently devalued or discarded, leading to substantial economic losses for growers (Campbell and Kelly 2002). In extreme cases, shellfish experience severe shell damage and mortality.

Mechanical interference

Mechanical interference from biofouling overgrowth can be so severe it compromises the opening of shellfish valves. Valve obstruction is often attributed to smothering fouling species, such as colonial tunicates, but also arises from three-dimensional, structure forming fouling species such as hydroids (eg *Ectopleura crocea*, Figure 1b), macroalgae and barnacles. Physical disruption to the opening and closing of valves and hinges results in ineffective feeding (de Sa et al. 2007). In oysters, interference competition has a major effect on respiration rates (Miyauti 1968) and can cause mortality (Dharmaraj et al. 1987). Internal parasitic fouling organisms are also problematic, causing impediment to feeding mechanisms and stress to shellfish. For example, the hydroid *Eutima japonica* inhabits juvenile scallops, reducing shell length growth by 43% and when accompanied by other stressors such as handling and transfers, may lead to mass mortalities (Baba et al. 2007).

Biological competition

Fouling species often compete with shellfish for food and space, resulting in decreased recruitment success, inhibited growth and reduced product value (Adams et al. 2011). Food availability strongly influences shellfish growth (Southgate and Beer 2000; Watson et al. 2009) and competition for food resources between shellfish and biofouling organisms can be significant (Le Blanc et al. 2003). Fouling organisms are primarily filter feeders and although the strength of their competitive interaction depends upon resource limitation and the species present, many foulers compete with farmed shellfish for food. The tunicate *C. intestinalis* and the mussel *Mytilus edulis* are suspension feeders with overlapping preferences in the size range of particles they consume (Daigle and Herbinger 2009). These organisms have very similar clearance rates and as such food competition may be substantial (Petersen 2007). Similarly, in oyster aquaculture, tunicates compete for phytoplankton, causing reduced growth (Rissgård et al. 1995). In addition to food competition, shellfish may experience competition for space and are particularly vulnerable to interference competition from overgrowth. For example, *Ectopleura larynx* can smother scallop shells and attach their shells together (Claereboudt et al. 1994), and overgrowth by colonial ascidians can reduce the feeding ability of mussels (Lesser et al. 1992).

Environmental modification

Biofouling affects aquaculture environments by reducing water flow and changing the concentrations of waste products. In oyster culture, biofouling reduces water currents and exchange, leading to rapid food depletion (Yukihira et al. 1998). Conversely, biofouling increases food availability to shellfish through enhanced net primary production (Lodeiros et al. 2002; Ross et al. 2002; Le Blanc et al. 2003). Biofoulers also greatly contribute to the already high biodeposition beneath aquaculture farms (Stenton-Dozey et al. 2001). For example, Giles et al. (2006) report that of the total deposition under a farm, only 14% can be attributed to mussel biodeposits, suggesting that the remaining 86% is deposited by other sources including biofouling. Similarly, the presence of *C. intestinalis* on cultured mussel lines increases biodeposition by a factor of two when compared to mussel lines without tunicate fouling (McKindsey et al. 2009). Biodeposition can significantly modify nutrient dynamics in the surrounding ecosystem, leading to an altered benthic community structure (Giles et al. 2006; Weise et al. 2009). In addition, the introduction of non-indigenous fouling species, which are thought to use aquaculture infrastructure as reservoirs to facilitate their spread, can have significant ecological effects on surrounding natural habitats (Ruesink et al. 2005; Rius et al. 2011). For example, *C. intestinalis*, a common non-indigenous fouling species in aquaculture settings, can fundamentally change the composition of sessile communities by depressing local species diversity and altering community assembly processes (Blum et al. 2007).

Increased weight and drag

Biofouling adds significant weight and drag to shellfish culture infrastructure, rapidly becoming a management issue. The need for additional flotation and repairs to equipment leads to subsequent increases in operational costs. In one of the few studies quantitatively measuring fouling in pearl culture, nets used to culture pearl oysters increased 5-fold in weight over a 6 month period due to heavy settlement by barnacles (Dharmaraj and Chellam 1983). Biofouling organisms cause increased drag through reduced water exchange (Claereboudt et al. 1994; Adams et al. 2011), and their presence can cause stock to drop from lines due to their additional weight, particularly in mussel culture (Mallet and Carver 2006). For example, heavy infestations of *C. intestinalis* add in excess of 10 kg m^{-1} of culture rope to commercial mussel lines, causing compromised attachment of mussel byssal threads and subsequent crop losses of 50–60% (Ramsay et al. 2008). While biofouling of equipment is important, it is secondary to the impact on the cultured animals themselves. However, this effect is reversed in finfish culture systems.

Fish

Biofouling growth on fish cages and infrastructure has three main negative effects: (1) restriction of water exchange due to the growth of fouling organisms causing net occlusion. When fish are held in high density in net pens, this leads to poor water quality as flushing is reduced. Lowered dissolved oxygen levels result and the removal of excess feed and waste is inhibited; (2) disease risk due to fouling communities acting as reservoirs for pathogenic microorganisms harboured by macro- or microbial fouling species on cage netting, or lowered dissolved oxygen levels from poor water exchange increasing the stress levels of fish, lowering immunity and increasing vulnerability to disease; (3) cage deformation and structural fatigue due to the extra weight imposed by fouling. The maintenance and loss of equipment directly contributes to production costs for the industry.

Restriction of water exchange

Occlusion of netting mesh and the subsequent restriction of water flow into and out of the cage environment is the key impact of biofouling on aquaculture nets. The flow of water through cages can be more than halved with significant biofouling loads (Gormican 1989). Flow also decreases when cages are aligned in the current (Inoue 1972). When cages are aligned in a series, and when netting becomes fouled, the effects combine synergistically to reduce water exchange (Aarsnes et al. 1990). Net pen sizes for salmonid aquaculture are increasing (Jensen et al. 2010) and nets are now held in the sea for the whole production cycle. Therefore, the effects of biofouling on water exchange are expected to become more severe because larger cages and nets have a smaller surface area to volume ratio and hence reduced rates of water exchange compared to smaller nets (Lader et al. 2008).

Water exchange replenishes dissolved oxygen (DO) and removes excess feed and waste. Maintaining DO levels is key to effective production (Oppedal et al. 2011a, 2011b) and low DO levels are problematic in modern production settings (Johansson et al. 2006, 2007). Reduced DO levels inside cages, and clear relationships between DO levels and short-term water exchange are well documented. As stocking densities increase, DO consumption increases (Oppedal et al. 2011a, 2011b). Consequently, a combination of low current flow and significant mesh occlusion, and a high stocking density of fish, will reduce DO rapidly (Johansson et al. 2006). Mortalities due to anoxia have been recorded in heavily fouled nets. Oxygen concentrations of >7 mg l^{-1} are recommended for salmon farming, whilst concentrations of <5 mg l^{-1} negatively impact on feeding, fish growth and respiration (Remen et al. 2012) and levels of <2 mg l^{-1} can result in mortality. Whilst oxygen levels within cages are primarily controlled by water exchange, oxygen production or consumption by fouling communities can affect DO levels (Cronin et al. 1999).

Disease risk

Fouling organisms and microbial communities on cage netting can present a health risk to cultured species by harbouring pathogenic microorganisms. Viral pathogens of finfish accumulate and persist for long periods within shellfish. Viruses isolated from bivalves and identified as finfish pathogens include 13p2 reovirus, the chum salmon virus, JOV-1 Japanese oyster virus, infectious pancreatic necrosis strains and infectious hematopoietic necrosis virus (Leong and Turner 1979; Meyers 1984). In addition, a number of bacterial agents that cause disease in finfish are common to bivalve tissues (eg *Vibrio* spp.). The occurrence of netpen liver disease (NLD) in caged fish is linked to the consumption of fouling organisms by the cultured species (Kent 1990; Andersen et al. 1993). NLD was thought to be caused by a hepatotoxin that may be produced by algae during summer (Kent 1990). The toxin isolated from affected liver tissue has been identified as microcystin-LR, a protein phosphatase inhibitor (Andersen et al. 1993). The fouling biota of the salmon cage is a reservoir for microcystin and the disease is likely to be contracted by feeding on net biota (Andersen et al. 1993).

Fish farms can also facilitate parasite life cycles by increasing the host density and promoting transmission from wild to cultured stocks and *vice versa*. Infection by *Gilquinia squali* metacestodes has been implicated in the deaths of Chinook salmon smolts at fish farms in British Columbia (Kent et al. 1991) where an unidentified crustacean which lives within the cage biofouling community likely acts as an intermediate host, and transfer to the definitive host (or the farmed salmon) occurs directly through ingestion (Kent et al. 1991). The life cycle of *Cardicola forsteri*, a major blood fluke pathogen of southern bluefin tuna (*Thunnus maccoyi*) in Australian aquaculture cages has an intermediate life history stage within polychaete biofoulers attached to the net pens, with other biofouling species acting as a reservoir of this parasite (Cribb et al. 2011).

Cage deformation and structural fatigue

Exposure to currents causes net cages to change their shape by deflection and deformation. The extent of the change in shape depends on current velocity, original shape and construction of the cage, placement weights, type of netting, and level of biofouling (Fredheim

2005; Lader et al. 2008). Increased mesh occlusion increases drag forces on netting; current-induced forces on a fouled net may be 12.5 times that of a clean net (Milne 1970). Consequently, unless cages are heavily weighted, the shape of the cage may be severely deformed by current flows of 0.5–1 m s^{-1}, reducing the effective cage volume by 45–80% (Osawa et al. 1985; Aarsnes et al. 1990). Reduced cage volumes impact on DO consumption, ammonia production will increase per unit volume, and crowding will stress the cultured fish (Lader et al. 2008).

Fouling biomass also increases static load on nets up to 200-fold (Milne 1972 in Beveridge 2004), and horizontal drag forces on cage netting can be increased by up to three times by common fouling hydroids and mussels (Swift et al. 2006). Highly deformed nets increase structural stresses on the cage at specific points, with a two to six-fold increase in horizontal forces in the cage corners (Tomi et al. 1979). Cage designers and operators need to account for these increased loads in the design of cage floatation and mooring systems or devastating net failures result which lead to escapes of fish (Jensen et al. 2010).

The control of biofouling in aquaculture

The negative and significant impacts that biofouling has on viability and profitability of aquaculture has necessitated a long and persistent effort in biofouling control. Historically, the aquaculture industry has borrowed antifouling (AF) technologies from other marine industries which focus on chemical AF technologies. AF paints to control biofouling are commonly used on surfaces in marine transport, oil and gas industries (Yebra et al. 2004; de Nys and Guenther 2009; Dürr and Watson 2010). These paints leach biocidal compounds such as heavy metals and organic biocides onto the surface, producing a thin, toxic layer which prevents the onset of biofouling. However, many of the chemicals and heavy metals involved are recognized as dangerous in the environment, with detrimental effects on the survival and growth of shellfish (Paul and Davies 1986; reviewed by Fent 2006) and fish (Lee et al. 1985; Short and Thrower 1986; Bruno and Ellis 1988) and this has prompted an effort to prevent or mitigate biofouling in aquaculture through alternative methods. Consequently, biofouling control remains one of the most difficult challenges and costly production issues facing the aquaculture industry.

Shellfish

Methods to avoid, mitigate or prevent the effects of biofouling in shellfish culture fall into five broad categories: (1) avoidance of natural recruitment to prevent settlement and growth of biofouling; (2) physical removal ranging from scrubbing and brushing to chemical dips and sprays; (3) biocontrol using natural species; (4) coatings on shells; (5) control and protection for equipment using antifouling coatings and organic biocides.

Avoidance of natural recruitment

Understanding the larval and settlement biology of problematic biofouling organisms offers the opportunity to manage an appropriate annual schedule of mitigation regimes to minimise colonisation by fouling species (Willis et al. 2011; Dunham and Marshall 2012). Avoidance techniques within farm practices provide a natural strategy to prevent or minimise larval recruitment of fouling organisms. For example, temporarily removing shellfish from the depth level favoured by fouling organisms during the peak period of settlement enables fewer larvae to colonise (Arakawa 1990). This strategy is questionable where fouling pressure is persistent, such as tropical regions, but can be a sensible and effective strategy for regions where fouling is predictable and seasonal. However, even then the practice may be ineffective at reducing fouling biomass (Le Blanc et al. 2003), prompting further techniques to decrease fouling settlement and growth by increasing stocking density of cultivated mussels during fouling episodes or by decreasing stocking density ('re-socking') of mussels after fouling episodes (Ramsay et al. 2008).

Physical removal

Given the adverse effects of chemical antifoulants on shellfish, the control of biofouling in shellfish culture must rely almost exclusively on the removal of fouling organisms. Methods of fouling removal, and the frequency and degree of effort required, are commonly dictated by the fouling composition or intensity of fouling outbreak at a given site (de Nys and Ison 2008; Mallet et al. 2009).

Air exposure of shellfish and associated infrastructure affected by biofouling has varying degrees of success depending on the composition of the fouling community (eg hard *vs* soft bodied organisms) and the varying sensitivities of shellfish species to air exposure (Gervis and Sims 1992). For example, calcareous organisms such as tube worms and barnacles can retain their internal moisture for long periods of time, so may be less affected. Similarly, some tunicates with a tough, leathery morphology can survive air exposure for many hours (Le Blanc et al. 2007), and under humid conditions, some algal species exposed to air can remain viable for several weeks (Forrest and Blakemore 2006).

Power washing to remove fouling organisms using mechanical equipment is a common method, with few negative implications for shellfish. It can improve the condition of oysters through increased growth in shells that are handled and cleaned regularly compared to uncleaned shells (Taylor et al. 1997). Washing reduces some organisms such as algal gametophytes (Forrest and Blakemore 2006) and reduces the abundance of some solitary tunicates by up to 80% (Mallet and Carver 2006). However, there are problems associated with its use to mitigate fouling by some colonial organisms, which may undergo fragmentation (Hopkins et al. 2011) and recolonise nearby infrastructure (Paetzold and Davidson 2010). Manual (non-mechanised) cleaning with knives, brushes and water pressure is generally used by the pearl oyster industry in countries such as French Polynesia, Japan and China (Mao Che et al. 1996).

Immersing fouled shellfish and infrastructure in freshwater is a simple, cheap and environmentally friendly technique, with few detrimental effects on the cultured shellfish (Denny 2008). Shellfish are tolerant of freshwater immersion to a limited degree by tightly closing their valves. This technique has been used to treat incursions of many fouling organisms, based on the principle that fouling organisms are more sensitive to treatment. For example, immersion of Akoya pearl oysters in fresh water effectively controls polychaete infestations without inducing oyster mortality (Velayudhan 1983). However, this method is ineffective in completely eliminating some fouling taxa, including various tunicates (Carver et al. 2003; Denny 2008), and can require exposure times of minutes to days depending on the life stage of the target organism (eg algal plantlets *vs* gametophytes; Forrest and Blakemore 2006). Exposures to brine solutions are similarly inconsistent, with the possibility of rapid mortality of some algal species through osmotic stress (Sharp et al. 2006), but poor success against some tunicates (Carver et al. 2003).

Heat treatment has been used to successfully combat problematic biofouling in many marine industries (eg Perepelizin and Boltovskoy 2011), and is appealing due to its benign environmental effects and ease of application (Rajagopal et al. 1995). Although calcareous taxa such as tube worms and barnacles can be more resistant to heated water (Blakemore and Forrest 2007), a range of common algal and invertebrate fouling organisms are negatively affected (Forrest and Blakemore 2006; Blakemore and Forrest 2007), although the technique can lead to some shellfish mortality (Carver et al. 2003).

Both spray and immersion techniques have been implemented extensively using acidic and alkaline chemicals. In mussel culture, low concentrations of acetic acid are particularly successful against soft-bodied tunicates and against algae (Le Blanc et al. 2007; Denny 2008; Piola et al. 2010), whether applied by immersion or spray techniques. However, some mussel mortality may be experienced (Carver et al. 2003; Le Blanc et al. 2007) and the application of acetic acid also affects non-target organisms and hampers naturally occurring biocontrol (Paetzold et al. 2008). Other acids used less commonly but with some success on tunicates are silicic, formic and citric acid (Denny 2008). The most common alkaline substance in use is lime, and treatment has been conducted using both quicklime (calcium oxide) and hydrated lime (calcium hydroxide). Lime is effective against tunicates (Carver et al. 2003; Denny 2008), but less successful against other fouling species (Piola et al. 2010). Chlorination using chlorine bleach kills arbitrarily, so its use as an effective eradication treatment is considered tenuous (Williams and Schroeder 2004). It has proven efficient against a range of fouling organisms (Denny 2008; Piola et al. 2010), yet has been found to have no impact on some tunicates (Carver et al. 2003).

Biological control

Biological control, where predation of pest species by other marine organisms is used to manage fouling levels, is a useful management strategy in small-scale shellfish culture. Natural control mechanisms negate the need for costly physical and chemical treatments, and are safer for the health and wellbeing of the shellfish and the growers. Examples from oyster culture include the use of periwinkles (Enright et al. 1983; Cigarria et al. 1998), crabs (Ross et al. 2004) and sea urchins (Lodeiros and García 2004; Ross et al. 2004; Epelbaum et al. 2009). However, ensuring mobile organisms such as these remain on culture infrastructure for extended time periods is challenging, particularly in mussel culture (Comeau et al. 2012). This may require modification of culture techniques such as the addition of protective cages around mussel socks for retention (Epelbaum et al. 2009). The use of biocontrol in large scale shellfish culture is therefore tenuous.

Coatings

The development of coatings technology to mitigate biofouling in shipping and on other marine infrastructure has incited developments in shell coating technology within the shellfish industry. Coating of live pearl oysters with a biodegradable, wax-based, impervious, non-toxic coating, were successful in treating oysters heavily infected with boring clionid sponges (de Nys and Ison 2004). Surface integrity lasts for 2 to 3 months after which it degrades. Its use may negate the need to cull infected oysters, but is unsuitable as a long-term AF control. However, coatings can be designed that can be effective in either reducing fouling, or alternatively facilitating the removal of fouling organisms during mechanical cleaning. This can then reduce the frequency of cleaning with significant reduction in infrastructure and operational costs (de Nys and Horne 2003; de Nys and Ison 2008).

Control and protection for equipment

Fouling prevention strategies for culture equipment such as ropes, floats, panels, nets and trays have traditionally used heavy metals including copper, nickel and tin. Unlike tributyltin and nickel, copper-based coatings remain in use despite their negative impacts on developing vertebrates and invertebrates (Oliva et al. 2007), and their ability to concentrate in shellfish tissues (Changsheng et al. 1990). The use of copper on equipment is discussed in detail below as this is the most common method of deterring the settlement and growth of fouling organisms on equipment used in finfish aquaculture. In a similar manner to equipment used in finfish culture, there are few if any alternatives available, given that low surface energy coatings are only effective under flow. Low surface energy coatings may, however, facilitate the release of fouling communities under regular physical cleaning, which is the main method for biofouling control in shellfish aquaculture, and as such may be an effective co-treatment option. Application and resilience under operational conditions are key criteria to successfully develop this approach for shellfish culture systems.

Fish

Commercial fish farm operations usually employ a multifaceted approach to controlling net fouling. This includes: (1) net changing and cleaning to remove fouling organisms and maintain water exchange; (2) chemical antifoulants such as copper to deter the recruitment of fouling organisms; and most recently (3) biological control using herbivorous fish or invertebrates to graze biofouling from the net surfaces.

Net changing and cleaning

Fish farmers in temperate and tropical regions frequently change or clean net pens to maintain water exchange when biofouling loads are heavy (5–8 days in summer in Australia: Hodson and Burke 1994; 8–14 days in Japan: Milne 1979; 14 days in Malaysia: Lee et al. 1985; 3–4 weeks in Canada: Menton and Allen 1991). Large meshed cages are changed or cleaned less frequently because of the greater amount of fouling required to occlude the mesh (tuna cages of 60–90 mm mesh cleaned every 6 months: Cronin et al. 1999). If the fouling is restricted to the upper area of the cage, the frequency of cleaning can sometimes be delayed by raising the top few metres of the net out of the water (Needham 1988). Net changing incurs a major cost to the industry, necessitating the purchase of a large number of nets and provision of dedicated net-changing and cleaning teams. Moreover, frequent net changing risks damage or loss of stock, and disturbs the feeding regimes of fish which may lower growth rates. Net changing is labour and capital-intensive, and boat-mounted hydraulic cranes are needed for large cages. Changed nets are usually left to compost for 1–2 weeks on-shore, followed by cleaning with high-pressure water hoses or automated washing machines (Cronin et al. 1999; Olafsen 2006). Washing procedures and net handling frequently damage netting and reduce its life-span. Consequently, after cleaning, nets are repaired.

As an alternative to net replacement, nets can be cleaned *in situ*, primarily with cleaning discs on Remote Operating Vehicles, or manually by divers. Underwater net cleaners are now in widespread use (eg Tasmania: Hodson et al. 1997; Norway: Guenther et al. 2009). Over half of Norway's salmon farms now undertake regular *in situ* cleaning (Olafsen 2006). Although frequent mechanical cleaning is expensive, the combination of this with other strategies can reduce biofouling control costs by up to 50% per m^2 of netting (CRAB 2004–2007). *In situ* cleaning is now almost fully automated and the dominant removal strategy in the largest fish farms. Problems remain however in that fouling remnants are invariably left after cleaning (Greene and Grizzle 2007), some of which can regrow quickly (Guenther et al. 2010). The washing process can also trigger larval release which leads to rapid recolonisation of nets (Carl et al. 2011), as well as fragmentation and regrowth of some colonial organisms (Carl et al. 2011; Hopkins et al. 2011). *In situ* cleaning may therefore be required frequently. Furthermore, brushing increases fouling problems because it scratches the mesh creating loose filaments, the morphology of which are ideal settlement substrata for some fouling species such as mussels (eg *Mytilus edulis*, Figure 1c; Alfaro and Jeffs 2002) and hydroids (eg *Ectopleura larynx*, Figure 1d; Carl et al. 2011). An alternative to washing may be concentrated, short term exposure of fouling species *in situ* to heated seawater or acetic acid solutions, which may kill the organisms and negate the need for harsh brushing (Guenther et al. 2011).

Chemical antifoulants

As copper is highly toxic to many marine invertebrates, particularly their larval stages, copper coatings have a long history of approved use in mariculture. For example, in 2005 a total of 261 tonnes of copper was sold to the aquaculture industry in Norway. Copper adds ~ 20–25% to the cost of a knotless nylon cage (Beveridge 2004). In temperate regions, nets must be coated each year, but the application of copper AF paint gives good protection for 6 months and is effective during summer when fouling is worst (reviewed in Braithwaite and McEvoy 2005; Braithwaite et al. 2007; reviewed in de Nys and Guenther 2009).

Copper has negative impacts on non-target organisms including macroalgae (Andersson and Kautsky 1996; Bond et al. 1999), microalgae (Lim et al. 2006), clams (Munari and Mistri 2007) and fish (Mochida et al. 2006). Relatively low concentrations of copper are harmful to fish and diverse effects have been reported from several toxicity studies (Brooks et al. 2008; Brooks and Waldock 2009; Thomas and Brooks 2010). Copper leaches out of impregnated nets into the water column and elevated concentrations of copper inside treated salmon pens have been recorded after net installation (Brooks 2000; Brooks and Mahnken 2003; Thomas and Brooks 2010). While some studies indicate that salmon raised in copper-treated nets do not bioaccumulate copper in muscle or liver tissue (Peterson et al. 1991; Solberg et al. 2002), industry best practice is to introduce fish into nets 1 month after newly coated nets are in position, to minimise any potential for bioaccumulation.

There are environmental concerns that copper bioaccumulates in sediments around fish farms and in non-target organisms (Miller 1998). Intestinal copper levels in the green sea urchin *Strongylocentrotus droebrachiensis* are elevated at salmon aquaculture sites (Chou et al. 2003), and copper bioaccumulates in the hepatopancreas of lobsters sampled near salmon farms (Chou et al. 2000). Given recent evidence on the effects of dissolved organic carbon (DOC) on the bioavailability of copper and its impacts on non-target species, the use of copper in areas with high levels of DOC may not be as detrimental as perceived. This is an area of ongoing and topical research (Brooks et al. 2008; Brooks and Waldock 2009; Thomas and Brooks 2010).

Copper is also used as the active ingredient in metal based nets. The use of copper alloys to construct nets is not new; however, recent innovations in the construction of nets with copper-zinc, copper-nickel and copper-silicon alloys has spurred renewed interest by fish farmers in their use in Chile, Australia, Japan and elsewhere. Despite the promising nature of this technology, there is no published evidence of the effects of copper nets on biofouling and possible benefits such as reductions in fish pathogens and increased oxygen levels in cages due to better water flow. Biofouling appears minimal on copper nets, but their use in the industry is hindered by their weight, failure and breakage through corrosion and relative expense compared to standard nylon mesh. New techniques to construct light-weight mesh alloys may drive greater use of this technology by industry as benefits begin to outweigh costs.

Importantly however, the perception of using copper as an AF compound, be it in a coating or with a net, is undesirable in an industry selling a food product from a ‘clean and green’ marketing perspective. Most countries are now reducing their use of copper-based AF. The European Commission is proposing to give copper a R50/R53 classification, based on the 67/548/EEC directive on dangerous substances, which recognizes that copper is toxic to aquatic organisms and may cause long-term adverse effects in the environment. The Norwegian aquaculture industry is moving towards a reduction in copper use, based on public perception of copper treatments having negative environmental impacts (Sandberg and Olafsen 2006).

Worldwide, there are a number of other biocides currently being used as antifoulants, albeit not necessarily in mariculture (Konstantinou 2006; Brooks and Waldock 2009; Thomas 2009), which are candidates to supplement or replace the use of copper as an antifoulant. The most commonly used biocides include Irgarol 1051 and Sea-Nine 211 (isothioazolinones) (Konstantinou 2006; Thomas 2009). Coatings using isothiazolinones as the sole biocide class have been successfully tested in Australia (Svane et al. 2006) but there is little peer-reviewed literature on the efficacy of other biocides trialled in an aquaculture context.

All countries have enforced their own national legislation regarding AF paint biocides, with a diverse range of requirements. The European Union’s (EU) Biocidal Products Directive (BPD) is currently reviewing all European AF paint biocides (98/8/EC), in order to harmonise legislation between countries and control the production, marketing and use of biocidal products, for the protection of humans and the environment (Pereira and Ankjaergaard 2009; Thomas 2009). To phase out the use of traditional, hazardous AF coatings based on heavy metals such as copper, the general trend in global AF research and development has therefore shifted to the creation of agents that are both effective and environmentally benign, as a consequence of their chemistry (non-toxic coatings) or their physical properties (eg fouling-release coatings and non-leaching biocides) (Callow and Callow 2009; Pereira and Ankjaergaard 2009; Scardino 2009; Webster and Chisholm 2010).

Biological control

An increase in profitability and sustainability could be achieved by the use of herbivorous fish or invertebrates to control fouling, yet to date attempts to do so have been largely small-scale or experimental in nature. The biological control concept is constrained by the variation in types of algal and invertebrate fouling, which suggests that only herbivores and omnivores with a broad dietary range will be successful control agents. Furthermore, it is likely that continuous grazing will provide an environment which selects for inedible species, thus only reducing the frequency of net changing. Biological control using herbivorous fish has to date only been effective in small cages (Kuwa 1984); no examples of this strategy exist for modern, large-scale fish farms. Invertebrate detritivores, such as the red sea cucumber *Parastichopus californicus*, have reduced fouling in salmon mariculture, although maintaining their position on the sides of cages is difficult in wave affected areas (Ahlgren 1998) where most salmon aquaculture occurs. The advantage of biological control with sea cucumbers is that they are a commercial crop in their own right, with strong demand in Asia (Conand and Sloan 1989). However, regardless of value, the use of biocontrol with invertebrates is experimental with significant challenges.

New strategies to control and mitigate biofouling in aquaculture

The development of AF technologies for aquaculture is underpinned by the development of new AF solutions for the marine transport industry where costs for biofouling are high. There are six recommended criteria for AF strategies in the aquaculture industry (Lewis 1994). Strategies should: (1) be effective against a broad range of fouling taxa; (2) be environmentally benign; (3) have no negative effects on the cultured species; (4) leave no residues in the cultured species; (5) be able to withstand on-shore handling and cleaning; and (6) be economically viable. These strategies need to underpin the development of new technologies for the large-scale prevention of fouling in both shellfish and fish production.

Shellfish

While many control strategies involve treatments after fouling communities have established, an alternate strategy to manage biofouling could be based on more accurate predictions of the occurrence of fouling episodes (Cyr et al. 2007). Prediction may enable avoidance and is a feasible option in many environments, especially where infrastructure can be moved in synchrony with fouling settlement peaks. In addition, with the production of hatchery reared mussel larvae, farmers can deploy their larval collecting ropes outside ‘normal’ collecting times, which may coincide with low fouling settlement periods. Most studies on biofouling in aquaculture, and particularly shellfish culture, have taken place in temperate regions and fewer data exist for tropical regions, where fouling pressure is constant and growth is rapid.

Control of biofouling will be facilitated through further research on spatial and temporal variation in the larval and settlement biology of fouling species, and their development on both shells and equipment. Determining key points for disruption of the settlement and metamorphosis process will assist development of new AF technologies. However, this will need to be tempered with an acknowledgement that such strategies are only likely to be effective where fouling is already seasonal and largely mono-specific. Ultimately, non-toxic alternatives to AF paints and coatings, that deter fouling episodes, are required and are a focus for research. For example, a novel technique, the application of food grade oil to farm buoys, ropes and floats, reduced fouling by algae and tunicates in mussel culture by more than 90% (Bakker et al. 2011). Fouling prevention rather than mitigation is obviously desirable, both ecologically and economically.

Farmed shellfish suffer more from endolithic biofouling than natural populations (Mao Che et al. 1996), suggesting that culturing techniques and fouling removal practices wear away the protective shell periostracum more quickly (Mao Che et al. 1996). While the periostracum does not deter all fouling species, it is broadly effective against boring organisms. Management of husbandry and cleaning regimes to prevent the removal of this natural coating would optimise the fouling resistant properties of shells and extend their efficacy (Mao Che et al. 1996; Guenther et al. 2006). Hard fouling such as barnacles, tube worms and bivalves are particularly difficult and costly to remove. The development of inert barrier based man-made coatings which prevent fouling organisms from settling and facilitate their removal could provide broader spectrum deterrence to fouling (de Nys and Ison 2004). When coated on pearl oysters, waxes and polyurethanes offer both deterrence and enhanced removal of fouling organisms (de Nys and Horne 2003). Similarly, low surface energy coatings are constantly improving with increased resilience and decreased flow required for the release of fouling organisms (Townsin and Anderson 2009). For example, release of fouling is said to occur at speeds as low as 10 knots. The broader shellfish industry would benefit by understanding the capacity of these coatings (derived from the marine transport industry) in delivering AF alternatives that meet the six criteria for success. Within this context, there are mechanisms that may enhance the efficacy of low surface energy coatings in deterring the initial settlement of fouling organisms by manipulating the topography of the low energy surface (Callow et al. 2002, reviewed by Magin et al. 2010). The development of novel surface microtopographies, many with a bio-inspired design, into low surface energy coatings may inhibit the settlement and growth of specific fouling organisms, and also facilitate their release (Scardino 2009; Aldred et al. 2010; Magin et al. 2010; Scardino and De Nys 2011).

While physical and mechanical cleaning is the corner stone of many large shellfish industries such as pearl oysters, the development of effective and inexpensive technology to remove biofouling mechanically is a key area of research in shellfish culture. For example, low-cost tools which mount outside traditional oyster stacks and move around the stack with currents and waves resulted in 16 times less fouling than traditional oyster stacks (Sala and Lucchetti 2008). Similarly, the novel addition of artificial growth medium (expanded clay aggregate) to basket cockle culture enclosures significantly reduced shell deformities and barnacle fouling as well as reducing fouling by tube worms, overall fouling rate, and fouling intensity (Dunham and Marshall 2012).

Biocontrol is another focus for research. Biocontrol is attractive as it can augment aquaculture industries when the species used for biological control also have commercial value, and may provide a potential complementary product through polyculture (Ross et al. 2004). Of particular focus are sea urchins, which may provide long-term financial benefits due to the availability of a diverse range of edible species with commercial value and their closed life cycle (reviewed in Lawrence 2007). While this methodology is unlikely to have broad spectrum use in highly mechanised industries, it warrants investment and consideration, with significant scope to deliver innovation and value.

Fish

The control of fouling on nets and other fish farm structures is largely restricted to a limited range of products which release copper and/or zinc and/or additional booster biocides. As metal and biocide based technologies are removed from the market, with a clear driver being the EU Biocides Directive (Pereira and Ankjaergaard 2009), the aquaculture industry may have to return to the traditional methods of net changes and washing. New products with a focus on fouling-release technologies based on low-surface energy coatings, texturing and surface-bound compounds could be developed. Fouling-release technologies rely on hydrodynamic forces to remove fouling organisms with poor adhesion to the fouling-release surface making them less suitable for aquaculture (see above). As the technology for vessels improves, the transfer (trickle-down) of technology to aquaculture industries will occur. New approaches for marine shipping and infrastructure are targeting well-documented pharmaceuticals (Pinori et al. 2011), bioactives (Dahlström and Elwing 2006; Pinori et al. 2011), and commercially available enzymes (Pettitt et al. 2004; Aldred et al. 2008) as antifoulants, or innovations with existing technologies such as copper (Vucko et al. 2012). These approaches may prove productive if they can be specifically tailored to aquaculture, however, they still involve a chemical entity and their use will attract close scrutiny of any chemical effects on cultured organisms.

Non-toxic coatings

Biocide-free, low surface energy siloxane elastomers and fluoropolymers may provide a non-toxic alternative to control biofouling in aquaculture given the step-wise improvements in their efficacy in the marine transport industry (Lewis 2009; Townsin and Anderson 2009; Magin et al. 2010; Webster and Chisholm 2010). These 'fouling-release' coatings aim at reducing or preventing the adhesion of fouling. Silicone-based paints are a non-toxic alternative to biocidal paints for ships' hulls, where the speed of the vessel produces the hydrodynamic shear required to remove weakly adhered fouling (Yebra et al. 2004; Townsin and Anderson 2009; Webster and Chisholm 2010). Although the hydrodynamic forces are much reduced in a 'stationary' aquaculture environment, nets and panels coated with non-toxic silicone coatings reduce the initial stages of fouling development and make it easier to clean the net of fouling that does accumulate (Hodson et al. 2000; Terlizzi et al. 2000). In addition, simple, but effective methods using an air-bubble curtain in conjunction with fouling-release coatings may also prove effective on aquaculture infrastructure (Scardino et al. 2009). A number of commercial products are available for aquaculture and the use of air bubble curtains is likely to yield commercial outcomes of great interest to the aquaculture industry in the medium to short-term as practical issues such as cost-effective coating of aquaculture nets are addressed. There are also further developments in the field of fouling-release technologies using the principles of super-hydrophobicity (Genzer and Efimenko 2006; Marmur 2006; Callow and Callow 2009; Scardino 2009). However, the commercial development of these technologies and their application to stationary aquaculture infrastructure will require a longer time frame.

Non-leaching biocides

Biocides irreversibly bound to the AF coating surface or net are known as non-leaching biocides. While this approach limits environmental contamination, it has not been successfully pursued. The techniques have been used effectively against bacterial biofouling on biomedical devices (Hume et al. 2004; Zhu et al. 2008) and this is an area of technical promise with the move towards legislation restricting antifouling technologies to non-release mechanisms.

Conclusion

The occurrence of biofouling in marine aquaculture is a significant management issue resulting in increased operational expenses and deleterious impacts on the species being cultured. Surprisingly, for an issue with such high impact in a growing global industry, sparse information exists on its effects and costs. For example, the focus on biofouling in cage culture has been skewed to more modern advanced aquaculture industries, such as the Northern hemisphere salmon industry, with little quantitative information on fouling in new aquaculture regions and in the tropics where fouling community development is most rapid. The expansion of tropical aquaculture and the trend towards greater use of offshore sites both present new challenges in understanding the impacts of fouling and implementing successful control measures. Given the limited choice of products currently available, quantitative studies on the spatial and temporal variation of fouling species, and the effects of husbandry techniques and farm management on fouling development, are essential to assist the industry to choose the most cost effective and practical methods for fouling control, both now and into the future. In terms of control, the mechanical removal of biofouling remains dominant in shellfish and fish culture, and copper coatings on fish nets are the only consistently effective form of biofouling prevention at an industrial scale. Future developments need to rely on incremental improvements in these fundamental platform technologies until there is a step-change in the development of non-toxic, low surface energy coatings. Low surface energy coatings fit all of the key criteria for a long term fouling control mechanism that meets strict legislative frameworks around the environment and food products. The development of robust low surface energy coatings that prevent fouling and facilitate its release at low water flows have the potential to transform biofouling control in aquaculture either independently, or in conjunction with mechanical cleaning. Notably, the development of biofouling technologies will always be led by larger, more valuable maritime industries, and the most advanced of these rely on moving structures to facilitate fouling release. However, as low surface energy coatings are developed and modified to provide fouling release at lower release velocities their application to aquaculture has the potential to transform the manner in which biofouling is controlled. Therefore, while the aquaculture industry remains a step behind other maritime industries in control methods it can also benefit from the broader research effort across maritime industries to solve a cosmopolitan, persistent and complex problem, biofouling.

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