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The drivers of sea lice management policies and how best to integrate them into a risk management strategy: An ecosystem approach to sea lice management

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Abstract

The control of sea lice infestations on cultivated Atlantic salmon is a major issue in many regions of the world. The numerous drivers which shape the priorities and objectives of the control strategies vary for different regions/jurisdictions. These range from the animal welfare and economic priorities of the producers, to the mitigation of any potential impacts on wild stocks. Veterinary ethics, environmental impacts of therapeutants, and impacts for organic certification of the produce are, amongst others, additional sets of factors which should be considered. Current best practice in both EU and international environmental law advocates a holistic ecosystem approach to assessment of impacts and risks. The issues of biosecurity and ethics, including the impacts on the stocks of species used as cleaner fish, are areas for inclusion in such a holistic ecosystem assessment. The Drivers, Pressures, State, Impacts, Responses (DPSIR) process is examined as a decision-making framework and potential applications to sea lice management are outlined. It is argued that this is required to underpin any integrated sea lice management (ISLM) strategy to balance pressures and outcomes and ensure a holistic approach to managing the issue of sea lice infestations on farmed stock on a medium to long-term basis.

KEYWORDS
aquaculture, Drivers, Pressures, State, Impacts, Responses DPSIR approach, integrated sea lice management, management, sea lice

1 | INTRODUCTION

Sea lice have long been regarded as having the most commercially damaging effect on cultured salmon in the world with major economic losses to the fish farming community resulting per annum (Bristow & Berland, 1991; Jackson & Costello, 1991; Liu & Bjelland, 2014). They affect salmon in a variety of ways: mainly by reducing fish growth, loss of scales which leaves the fish open to secondary infections (Wootten, Smith, & Needham, 1982) and damaging of fish which reduces marketability, but also by increased levels of morbidity and mortality (O'Donohoe et al., 2008). The control of sea lice has been an issue for salmon farmers almost as the inception of intensive farming practices in the 1970s (Brandal & Egidius, 1979; Brandal, Egidius, & Romslo, 1976; Hogans & Trudeau, 1989). In British Columbia, in the North Pacific veterinarians do not consider *Lepeophtheirus salmonis* to be a serious health concern on farmed Atlantic salmon. This may be related to the differences between Pacific and Atlantic populations of *L. salmonis* with Pacific populations showing less virulence to Atlantic salmon (Saksida, Morrison, Sheppard, & Keith, 2011). As the industry developed the importance of sea lice control increased and by the late 1980s sea lice infestation was widely regarded as the most important issue affecting fish health in farmed salmon and giving rise to significant losses in production (Jackson & Costello, 1991; Pike, 1989; Tully, 1989). Most of the damage caused by these parasites is thought to be mechanical, carried out during the course of attachment and feeding (Brandal et al., 1976; Jones, Sommerville, & Bron, 1990). Inflammation and hyperplasia have been recorded in Atlantic salmon in response to infections with *L. salmonis* (Jones et al., 1990; Jonsdottir, Bron, Wooten, & Turnbull, 1992; Nolan et al., 2000). Increases in stress hormones caused by infestations have been suggested to increase the susceptibility of fish to infectious diseases (MacKinnon, 1998). Severe erosion around the head caused by heavy infestations of *L. salmonis* has been recorded previously (Berland, 1993; Pike, 1989). This is thought to occur because of the rich supply of mucus secreted by mucous cell-lined ducts in that region (Nolan, Reilly, & Wendelaar Bonga, 1999).

Criticism of the salmon farming industry for how they have handled the salmon louse problem has influenced the design of regulations and licences to operate. For example in Norway, concerns with respect to salmon lice led to a postponed implementation and possibly abandonment of an increase in the maximum allowable biomass (Asche & Bjørndal, 2011; Torrissen et al., 2013). The strong negative publicity in respect of the sea lice issue may also influence the public opinion and have a negative effect on the public perception of aquaculture. In Norway inadvertent accumulation of sea lice from fish farms and genetic interactions with farmed escapees have been identified as the two primary challenges with respect to interactions with wild salmon populations (Glover et al., 2017; Taranger et al., 2015). These concerns have led to the requirement, based on the precautionary principle, to avoid and mitigate impacts of sea lice of fish farm origin on wild stocks being a major driver of sea lice control programmes for farmed salmon (Jackson, 2011) in many jurisdictions.

Control of sea lice infestations continues to be a major issue in many regions of the world. Drivers of priorities and objectives vary for different regions and even between jurisdictions in the same ecoregions. Ecosystems vary in terms of host species and the species of parasite. In the Northern Hemisphere *Lepeophtheirus salmonis* is regarded as the more serious parasite of the two species which affect farmed salmon (Helgesen, Romstad, Aaen, & Horsberg, 2015; Jackson & Minchin, 1992; Rae, 2002). In the Pacific Northwest, whilst the parasite is *L. salmonis* and the farmed host is normally the Atlantic salmon (*Salmo salar*) the host parasite dynamic is complicated by the existence of large numbers of wild hosts comprising several different species of the genus *Oncorhynchus* (Brooks, 2009). In Chile the parasite species is *Caligus rogercresseyi* which infests a number of native species including the small eyed flounder (*Paralichthys microps*) and the Silverside smelt (*Odontesthes regia*) as well as farmed Atlantic salmon. This species is widely distributed in southern Chile, and is considered a serious threat to this industry (Hamilton-West et al., 2012).

The context for management strategies has also been undergoing radical revision as the scale and complexity of the salmon farming industry has grown. There has been an evolution of management strategies from a focus on treating individual cages to synchronous treatments of whole sites and also sophisticated treatment plans covering whole bays (Jackson, 2011; Jackson, Hasett, & Copley, 2002; Murray & Gubbins, 2016). There have also been initiatives to develop integrated pest management strategies including the use of biological controls such as cleaner fish (Deady, Varian, & Fives, 1995) and targeted control at key times and in key locations (Brooks, 2009; Jackson et al., 2002). However, this evolution has rarely been strategic and in many cases has been reactive responding to a variety of pressures from fish health, to environmental concerns over the impacts of treatments on non-target organisms such as commercially important species including shrimp and lobster (Burridge, 2013) and the potential impacts on stocks of wild salmonids. Salmon farming is a relatively new form of farming in a relatively new sector, aquaculture. Land based food culture has evolved over millennia and underwent a radical transformation during the agricultural revolution, leading to massive changes in technology, husbandry techniques and production volumes. These developments resulted in fundamental changes in the approach to a whole range of issues including parasite control and animal health. The scale of the aquaculture industry and in particular salmon farming has been rapidly increasing in recent decades (Figure 1). It has grown from a small niche industry to become what is now a global scale sector. Farmed Atlantic salmon production in 2014 exceeded 2.3 million tonnes and the species was ranked as number eight by amount for cultured fish species produced globally (Glover et al., 2017) accounting for more than 99% of all human consumption of salmon (FAO, 2016). Salmon farming is now one of the world's most economically important industries in the marine food sector.

2 | CURRENT MANAGEMENT PRACTICES AND THE NEED FOR A CONCEPTUAL EVOLUTION

Currently lice management strategies in most parts of the world including Ireland, Scotland (Anon. 2007, 2015), Canada (Saksida et al., 2011), the Faroes (Anon. 2013) and Norway are governed by protocols or plans developed at a local, regional or even national level (Anon, 2008; Jackson, 2011). In some cases these national plans are guided by risk assessments (Department of Agriculture

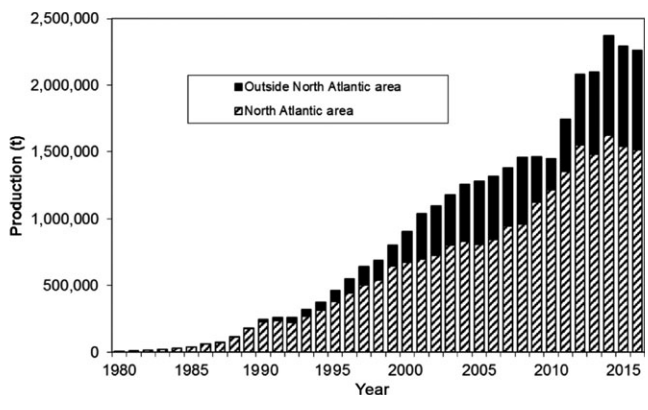

FIGURE 1 Growth in global salmon production

Fisheries & Food, 2008; Taranger et al., 2015). The requirement to ensure sustainability and mitigate environmental impacts features in most if not all management regimes but in most cases it is not integrated in a structured or ecosystem-based management framework. The concept of ecosystem-based management has been developed in respect of wild capture fisheries in response to the unintended negative consequences of the total allowable catch system and associated quotas which were for several decades the basis of international fisheries management. In essence the ecosystem approach seeks to ensure that all negative impacts, both on non-target organisms and on sensitive habitats and food webs are taken into account in the setting of limitations on harvesting and/or management activities. Such frameworks are being developed (Arthur, 2008) and applied increasingly in other sectors and are leading to re-evaluations of management and risk assessment criteria (Berg, Furhaupter, Teixeira, Uusitalo, & Zampoukas, 2015). As the industry continues to develop and in particular if it is to reach the goals set out by the FAO (2016) as part of their *Blue Growth* initiative where they forecast that surging demand for fish and fishery products will mainly be met by growth in supply from aquaculture production, which is expected to reach 102 million tonnes by 2025 the adoption of such frameworks will be key to addressing the challenges in adopting suitable governance and regulatory frameworks.

A component of this evolution will be a move away from a reliance on medicinal treatments and chemotherapeutants to manage sea lice infections. In most salmon farming areas, widespread use of chemotherapeutants even where this has been part of a well coordinated treatment plan has led to reduced sensitivity or even resistance to treatment (Carmichael, Bron, & Taggart, 2013; Jones, Sommerville, & Wotten, 1992; Lees, Baillie, Gettinby, & Revie, 2008; Rae, 2002; Roth, Richards, Dobson, & Rae, 1996; Sevatdal, Copley, Wallace, Jackson, & Horsberg, 2005; Treasurer, Wadsworth, & Grant, 2000). From 2009 to 2015, the use of chemotherapeutants for lice treatments has increased. This best illustrated by the figures from Norway (Table 1). Except for the flubenzurones, in Norway all approved chemotherapeutants now show reduced effect, including hydrogen peroxide. Concerns have also been voiced about increasing the sea lice's freshwater tolerance through freshwater treatments and the potential for selecting for increased virulence through farm management practices (Ugelvik, Skorping, Moberg, & Mennerat, 2017). Genetic studies have shown that resistance has the potential to spread rapidly throughout the north Atlantic salmon lice populations (Besnier et al., 2014). Thus, it can be assumed that the resistance situation seen in Norway may develop at any time in the rest of the north Atlantic salmon farming industry, and represents a threat to the development of the industry (Aaen, Helgesen, Bakke, Kaur, & Horsberg, 2015). There are a number of ways to maintain effective medical treatments using currently approved and available medicines; these include increasing the dosage level and using the drugs off-label and use of combination treatments of two or more therapeutants. In reality, both approaches have been practised. Both these approaches must be considered problematic from a risk assessment standpoint, as the authorities must approve of combinations of therapeutants, through an assessment of the associated environmental and animal welfare implications. In Norway, as is the case in Ireland and other EU member states, each individual chemotherapeutant must have an authorization approved by the Medical Products Agency. Similarly, if two or more treatments are to be used in combination, new approval is required. Whilst there are many studies investigating the effect of commonly used chemotherapeutants, effects on non-target species of drugs used in combinations are at best poorly understood.

Since 2007, there has been a focus on using a combination of azamethiphos and pyrethroids (deltamethrin/cypermethrin), which has been shown to have an increased effect on salmon lice, as compared to being used separately. The toxicity of a combination solution of azamethiphos and deltamethrin was assessed in a laboratory study on two species of crustaceans; the chameleon shrimp (*Praunus flexuosus*) and grass prawn (*Palaemon elegans*; Brokke, 2015). This is the first toxicity study where azamethiphos and deltamethrin were tested in combination. The survey was based on a concentration ratio between azamethiphos and deltamethrin of 60:1 when the two drugs were used together. Both species were exposed for 1 and 24 hr and further observed for an additional 24 hr. Both the common prawn and purse shrimp were significantly more sensitive to the drugs when used in combination. This study showed that non-target species may experience increased mortality from combination treatments as compared to treatments where therapeutants are used separately.

The current situation in respect of reduced efficacy to key therapeutants in certain farming areas has spurred the development, and use of a number of non-medical treatments. These include physical

TABLE 1 Chemotherapeutants used in sea lice treatments in Norway from 2004 to 2015

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Azamethiphos					66	1,884	3,346	2,437	4,059	3,037	4,630	3,904
Cypermethrin	55	45	49	30	32	88	107	48	232	211	162	85
Deltamethrin	17	16	23	29	39	62	61	54	121	136	158	115
Diflubenzuron						1,413	1,839	704	1,611	3,264	5,016	5,896
Emamectin	32	39	60	73	81	41	22	105	36	51	172	259
Teflubenzuron						2,028	1,080	26	751	1,704	2,674	2,509
Total	104	100	132	132	218	5,516	6,455	3,374	6,810	8,403	12,812	12,768
Hydrogen peroxide (tons)						308	3,071	3,144	2,538	8,262	31,577	43,246

removal, cleaner fish, and use of freshwater or other high tech solutions including the use of lasers and “snorkel barriers” (Stien et al., 2016). Sletmoen (2016) gives a useful review of some of the more recent initiatives currently under development. However, at present, the salmon farming industry still depends largely on use of pharmaceuticals as the basis for delousing strategies. There are ongoing efforts to develop effective ways to work around problems related to resistance or increased tolerance. These include integrated pest management approaches combining husbandry techniques with the use of cleaner fish and reduced use of treatments. The incentive to gain organic status for produce and the associated price premium has helped to encourage and facilitate these developments. Early efforts to use cleaner fish centred on the use of wild caught wrasse and were initially very successful (Deady et al., 1995; Sayer, Treasurer, & Costello, 1996) but difficulties with over winter survival of wrasse, biosecurity fears in terms of transfer of pathogens from the wild caught wrasse and a lack of well-developed husbandry practices for wrasse led to the discontinuation of their use. In the last decade there has been a resurgence in the use of cleaner fish with both wrasse and lump suckers (*Cyclopterus lumpus*) being utilized very successfully (Ottesen, Treasurer, FitzGerald, Maguire, & Rebours, 2012). There have been developments in the culture of both wrasse (D’Arcy et al., 2012) and lump sucker (Bolton-Warberg, M. Pers. Comm.) and the husbandry and animal welfare protocols for cleaner fish use are much better developed. The effective use of such biological control methods as a means of reducing reliance on treatments is a vital component of an integrated pest management strategy.

3 | RISK ANALYSIS TOWARDS AN ECOSYSTEM-BASED MANAGEMENT APPROACH TO SEA LICE INFESTATION

Both the aquaculture industry and its regulators must make decisions which could potentially have major consequences based on incomplete knowledge and with varying degrees of uncertainty. Use of risk analysis in aquaculture development and management is relatively new (Bondad-Reantaso, Arthur, & Subasinghe, 2008). Nevertheless, several protocols exist for estimating environmental risks arising from aquaculture. NOAA developed guidelines for ecological risk assessment of marine fish aquaculture in 2005 (Nash, Burbridge, & Volkman, 2005). This work was further developed by FAO (Nash, Burbridge, & Volkman, 2008) who presented broader guidelines for understanding and applying risk analysis in aquaculture in 2008. The same year GESAMP (Anon., 2008) provided guidelines on environmental risk assessment and communication in coastal aquaculture. The challenge posed in respect of the management of sea lice infestation is the balancing of one potential hazard, the risk of adverse environmental impacts from the increased use of chemical therapeutants for treatment of sea lice in marine salmon aquaculture, against multiple other risks including, animal welfare, the potential for impacts on wild fish stocks and the requirement to conserve the efficacy of available active compounds by limiting resistance development.

These frameworks for risk analysis have been described under the general heading of Driver, Pressure, State, Impact, Response (DPSIR) and are used by many as a methodological approach to assessing complex risk matrices. Phillips and Subasinghe (2008) identifies three different approaches to identification of hazards; single site—range of risks; single hazard—several exposure scenarios; and multiple hazards—multiple risks. Gregory, Atkins, Burdon, and Elliot (2013) propose the use of the DPSIR approach as a suitable modelling framework for problem structuring for marine management. The DPSIR approach seeks to balance pressures and to manage outcomes and therefore advocates a flexible system of decision-making, guided by individual risk assessments of the cost/benefit of action/inaction. The tool was developed to analyse environmental problems arising from human activities with an objective to assist in achieving sustainable development (Gari, Newton, & Icely, 2015). The European Environment Agency also advocates the use of DPSIR as an appropriate decision-making aid (European Environment Agency, 2014). The DPSIR approach (Figure 2.) provides a framework to assess the causes, consequences and responses to change in a complex adaptive system in a systematic way. It also provides a basis for linking policy objectives, environmental risks, benefits and local needs in a decision-making tool. Krause et al. (2015) argue for a similar type of iterative feedback process to address the information and knowledge exchange gap which exists between policy makers and the other stakeholders in the aquaculture sector at a global level. Such a tool would provide an objective framework within which to develop risk assessments such as the current model employed in Norway (Taranger et al., 2015). This concept is set out graphically in Figure 3. The key elements of this framework in respect of sea lice management are as follows: fish health and welfare (Bergqvist & Gunnarsson, 2013; Huntingford et al., 2006; Stien, 2013; Turnbull, Bell, Adams, Bron, & Huntingford, 2005), environmental impacts of therapeutants (Haya, Burridge, & Chang, 2001), protection of wild stocks (Taranger et al., 2015), avoidance of resistance development (Aaen et al., 2015), production standards including organic status. In this scenario fish, health and welfare and production standards are Drivers. Impacts on the environment and interactions with wild stocks are Pressures with possible impacts. The Impacts and State parameters would include resistance development, impacts on non-target organisms and damage to wild stocks. Assessment of the relative risks under each of these headings will inform the appropriate Response in each case. This framework allows for a more holistic and case-specific approach to the management of this very important parasite and is an appropriate framework for implementing an integrated sea lice management (ISLM) strategy. An integrated sea lice management strategy where husbandry and technological solutions are the main tools to control the parasite and medicines and chemotherapeutants are only employed when required and in limited circumstances is the objective. To be successful, this will require a more nuanced approach to management in terms of the timing of control activities, the thresholds at which controls are applied and the responses to difficulties in maintaining control.

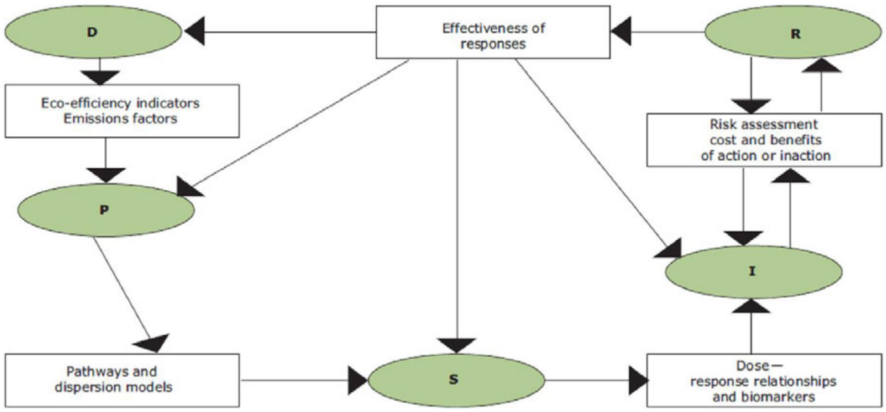

FIGURE 2 The Driver, Pressure, State, Impact, Response (DPSIR) approach as set out by European Environment Agency (2014). This tool is advocated by the EEA as an appropriate decision-making aid. The DPSIR approach provides a framework to assess the causes, consequences and responses to change in a complex adaptive system in a systematic way. It also provides a basis for linking policy objectives, environmental risks, benefits and local needs in a decision-making tool [Colour figure can be viewed at wileyonlinelibrary.com]

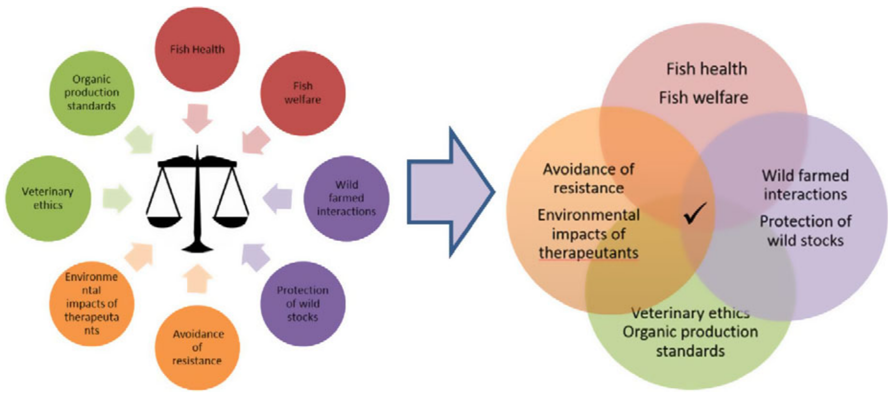

FIGURE 3 Graphical representation of the use of a Driver, Pressure, State, Impact, Response (DPSIR)-based process to underpin the development of an appropriate ISLM strategy on a bay by bay or control area basis. The development of a DPSIR tool to underpin specific ISLM programmes will provide a framework which can facilitate an evidence-based decision-making process capable of assessing competing pressures and impacts and providing balanced and objective advice to managers and decision-makers. Such an objective framework will be fundamental to advancing aquaculture production globally [Colour figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSIONS

To underpin any integrated sea lice management (ISLM) approach on a medium to long-term basis, it is necessary to balance pressures and outcomes and ensure a holistic approach to determining appropriate responses when managing sea lice infestations on farmed stock. We argue that a robust and sustainable approach to sea lice management which will be fit for purpose for a global salmon farming sector requires a problem structuring methodology such a DPSIR. The development of a DPSIR tool to underpin specific ISLM programmes for individual bays or control areas can provide an objective and evidence-based decision-making process capable of assessing competing pressures and impacts and providing balanced advice to managers and decision-makers. Such a framework will be fundamental to advancing aquaculture production, to promote policies and good practices for farming of fish, shellfish and aquatic plants in a responsible and sustainable manner as set out in the FAO Blue Growth Initiative (FAO, 2016) and addressing the key challenges identified by the European Union to the sustainable development of European aquaculture (Lane, Hough, & Bostock, 2014).

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