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Controlling emerging infectious diseases in salmon aquaculture

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Summary

In this paper, the authors review the impacts of diseases facing salmon aquaculture, drawing lessons from terrestrial animal diseases. They discuss the implementation of current control strategies, taking into account transmission patterns (vertical vs. horizontal), disease reservoirs, and interactions with wild fish. In addition, the decision-making context of aquatic disease control and the institutional organisation of control strategies are considered, with particular emphasis on the roles and responsibilities of regulatory authorities and the private sector. Case studies on the emergence and control of infectious salmon anaemia worldwide and pancreas disease in Norway are used to examine some of the controversies that may influence decision making and provide lessons for the future.

Keywords

Aquaculture – Control strategy – Disease control – Emerging disease – Institutional organisation – Salmon.

Introduction

The aquaculture industry provides an increasingly important source of protein for human consumption (1). The industry has taken a more pronounced role in providing fish for global diets, given the increasing demand for fish products worldwide and a stable or diminishing catch from wild fisheries (2). Globally, Atlantic salmon (*Salmo salar* L.) is one of the most intensely farmed and highest valued fish, with the majority of the world's production taking place in Norway, Chile, the United Kingdom and Canada (Fig. 1). Farmed Atlantic salmon is also a biologically efficient source of food and animal protein, with a low feed-conversion ratio and small carbon footprint (4).

However, the global salmon sector is increasingly threatened by emerging infectious diseases, which have caused substantial problems and costs for the industry (5, 6, 7, 8). Infectious salmon anaemia (ISA), caused by the ISA virus (ISAV; family *Orthomyxoviridae*), is notifiable to the World Organisation for Animal Health (OIE) (listed in 1990) (9) and primarily affects Atlantic salmon. Other than Australia, ISA has been described in every country in which salmon farming is intensively practised, including Norway (where ISA was first described in 1984), Canada (1996), Scotland (1998), the Faroe Islands (2000), the United States (2001) and Chile (2007) (10, 11, 12, 13, 14, 15, 16). Outbreaks of ISA are associated with large economic costs in affected countries (17, 18, 19). Pancreas disease (PD) is a viral disease caused by a salmonid alphavirus (SAV) (20). In Norway, more than 100 salmon farms annually have reported PD outbreaks in recent years (Fig. 2). Like ISA, PD results in large economic costs to the salmon industry (7); the disease is endemic in western areas of Norway, Scotland and Ireland (21, 22, 23, 24), but exotic outside Europe. Heart and skeletal muscle inflammation, caused by piscine orthoreovirus, was first described in Norway in 1999 (25, 26) and has been recorded in approximately 150 salmon farms annually (Fig. 2). Amoebic gill disease, caused by the parasite *Neoparamoeba perurans*, has emerged in Scotland after it was first reported in 2006 (27). Salmonid rickettsial septicaemia or piscirickettsiosis (28), caused by *Piscirickettsia salmonis*, is sporadic in Norway and endemic in Chile, and is responsible for about 50.5–97.2% of the total disease-specific salmon mortality in the Chilean industry (29). By contrast, several diseases that were once associated with severe losses are currently quite effectively controlled in many salmon-producing countries. The diseases that are being managed successfully include vibrosis (*Listonella anguillarum)*, cold-water vibrosis (*Allivibrio salmonicida*), furunculosis (*Aeromonas salmonicid*a), bacterial kidney disease (*Renibacterium salmoninarum*), and to some degree infectious pancreas necrosis (*Birnaviridae)* and infectious haematopoietic necrosis (*Rhabdoviridae)*.

An important global research gap remains in identifying cost-effective disease control strategies that not only can reduce the risk and magnitude of aquatic diseases, but also take into account the multitude of economic, social, environmental, and institutional ramifications of such measures. The literature on the economic impact of aquatic diseases (7, 30, 31, 32, 33) has primarily focused on the costs associated with disease, rather than improving the cost-effectiveness of decision making. Past reviews of terrestrial animal diseases (34) provide some guidance on models and methods, though aquaculture has specific characteristics and peculiarities that are not addressed by terrestrial methods. This paper seeks to redress these gaps, highlighting current disease control practices in the salmon aquaculture sector and the complications associated with current disease control protocols, and assessing lessons learned from terrestrial disease control. The authors use ISA worldwide and PD in Norway as examples to illustrate the discussion.

Characteristics of Atlantic salmon aquaculture and the emergence of infectious diseases

The Atlantic salmon industry combines intensive farming and interactions with the marine environment. Marine production takes place in semi-open marine net pens, where local currents drive the exchange of water and the dispersion of biological waste and infectious agents. As a result, the industry is constantly prone to disease outbreaks (Fig. 3) and the proximity of infected farms increases the risk of disease, e.g. ISA (35, 36, 37, 38, 39, 40) and PD (41). Disease outbreak is defined in the OIE *Aquatic Animal Health Code* as the occurrence of one or more aquatic animals infected by a pathogenic agent, with or without clinical signs, in an epidemiological unit (42). An epidemiological unit in this context is a group of fish sharing approximately the same risk of disease, such as a salmon farm. A framework for understanding the potential for emerging disease in aquaculture is described by Murray and Peeler (2005) (43). Highlights from that research include the importance of movements of live fish and eggs as reservoirs of the infectious agent, interactions of wild fish and other animals with farmed fish, the evolution of infectious agents affecting aquatic species, host specificity for the diseases, and poor management or an environment that increase the susceptibility of farmed fish to disease. In addition, aquatic diseases are mediated by differing types of transmission pattern (vertical vs. horizontal), affecting both disease emergence and its effective control.

Control strategies and control tools used in aquaculture infectious disease control

Control strategies

'Control' in a disease-controlling context is a general term describing the reduction in morbidity and mortality from disease, and encompasses all preventive and treatment measures taken to interfere with disease appearance (44). The management of infectious diseases in aquaculture can be classified into three basic strategies:

i) controlling by eradication, i.e. eliminating the infectious agent from the area or reducing the infectious agent to minute levels

ii) controlling the disease, but living with the infectious agent

iii) no control, but handling the recurrent costs associated with the disease (44).

The choice of strategy depends on a number of factors, such as the resources available, likelihood of success, support among stakeholders, disease characteristics and legislation (44). The choice between strategies (i) and (ii) requires an understanding by the organisation of the differences between them, in terms of knowledge requirements, costs and cost-sharing protocols.

An emergency disease refers to an exotic disease or a disease present within national boundaries with impacts considered of national importance (45). Emergency diseases are often controlled through the first of these strategies, which means that control measures are aimed at eradicating the infectious agent and the associated disease and reducing the biological impacts to zero or as near zero as possible (e.g. ISA) (Fig. 4). This is in contrast to diseases where the infectious agent will always be present (e.g. salmonid rickettsial septicaemia, salmon lice infestation, vibrio bacteria infection), where the aim is to reduce disease impacts to a cost-effective level (Fig. 4). For salmon lice infestation, the cost-effective level is usually measured in terms of its negative effects on populations of wild salmonids (47, 48).

Certain diseases that have severe trade implications are listed by governments in order to obtain legal rights to implement disease surveillance and control measures, and re-establish international trade. Diseases without trade restrictions may also be listed and subject to governmental jurisdiction if they are associated with severe social impacts or public-good interactions (e.g. salmon lice in Norway). Controlling such diseases is a benefit to society and thus merits public interventions (49). Salmon producers usually control non-listed diseases for commercial reasons, but may still receive some direct or indirect governmental support (44).

A disease control programme should include clearly defined objectives and rationale, an implementation plan, effective surveillance programmes and outbreak investigations, an emergency action plan, and measures for monitoring, evaluating and, if necessary, adapting the programme (50). Other important associated aspects to consider when developing such a programme may relate to the distribution of costs, benefits, risk and responsibility between all stakeholders; disease knowledge; diagnostic feasibility; veterinary infrastructure; the adequacy of legislation and the provision of compensation. It will also be necessary to have a thorough understanding of stakeholder incentives (44, 50). In aquaculture, pre-prepared standardised action plans are of key importance to ensure rapid action and improve disease control (51). Depending on the characteristics and importance of the disease, a range of tools and management plans can be enacted.

Control tools

Many infectious diseases in salmon farming are effectively controlled by the use of different combinations of control tools, each being either a preventive or a treatment measure, which together may have additive effects (44, 52). These tools include chemical treatments, vaccination, the development of genetic resistance through breeding, and zoosanitary control measures, each of which varies in cost, effectiveness and duration (52). Chemical treatments, for example, work instantaneously but are costly to administer, can have negative impacts on nearby ecosystems and can lead to the development of resistant pathogens (52, 53, 54, 55). Oil-based polyvalent vaccines injected intraperitoneally are highly efficacious against several bacterial diseases (e.g. furunculosis, vibriosis, cold-water vibriosis) in the short term, but require significant resources over time in both vaccine development and administration (52). Intraperitoneally injected vaccines also result in adverse biological side effects (56). Vaccines against some viral diseases are available but are currently not as effective as vaccines against bacterial diseases (57). Improvement of genetic resistance through breeding typically requires a long-term perspective and significant investment, and may require advanced technology (52). Zoosanitary measures include management practices that reduce the opportunities for infectious agents to spread from, into or inside salmon farms; such measures include fallowing, movement restrictions, surveillance, waste management and/or disinfection. These measures have the advantage of being applicable even with limited knowledge of the causes of disease, and are effective against several types of infectious agent (52). Surveillance can facilitate the early detection of pathogens and disease, thus enabling early intervention, although the sensitivity of detection is linked to both the technology used (e.g. polymerase chain reaction, histopathology) and the resources allocated for surveillance (58, 59).

The choice of control measures is highly sensitive to the characteristics of the disease, but should also take cost-effectiveness into account, including the long-term benefits of a disease control programme (50). As discussed below, institutional cooperation in the public and private sectors is crucial in disease management and research.

Organisation and challenges of disease control in aquaculture settings

Stakeholders in aquaculture disease control

Emerging infectious diseases, especially those disseminated by horizontal transmission by sea currents, are technically challenging to control. A further challenge is that salmon aquaculture involves a privately owned resource (salmon pens/farms) interacting with a common resource shared by many users (the marine environment). These complex interactions and dynamics make it difficult to find institutional arrangements that are perceived by all users as legitimate, fair and effective in all circumstances. Moreover, the public and private sectors are subject to different incentives for animal disease management. At a private-industry level, the decision-making context in fish farming is characterised by uncertainty, disagreement about facts and reliance on experiential knowledge, but is also one in which economic profitability takes precedence (60). Government is also subject to an uncertain and politicised decision-making context and has objectives that often compete with the industry in terms of environmental preservation, maintenance of wild fish stocks and social sustainability of industries; these objectives may vary by region and/or political influence of lobbying groups. Consequently, the actions taken by the public sector may reduce the profitability of private business. Other stakeholders are also involved, including environmentalists, the media, and rural communities that depend on the salmon industry, each of which has their own value systems and their own perspectives on what they consider to be 'optimal' disease management. At the same time, interactions within and across all of these groups, and with the environment (e.g. wild salmon), further complicate the disease control calculus, making the alignment of private incentives with the public good challenging at best (61).

The decision-making context of disease control

Interviews conducted with fish farmers, governmental agencies and veterinarians on disease control strategies in Norwegian aquaculture (60) have portrayed the decision-making context that fish farmers are caught in as marked by uncertainty, high interdependence with other stakeholders and a politicised public agenda (62, 63). Knowledge gaps related to disease properties and/or the effect of control measures can further prevent farmers from making cost-effective decisions and compel them to rely more on experiential knowledge (60).

Fish farmers are obliged to report to government if they suspect a listed disease. However, diseases may be difficult to detect in a net pen of 200,000 fish, where small increases in mortality, reduction in food intake or changed swimming patterns may arouse suspicion of disease. It may take time for a fish farmer to understand the situation and receive answers from veterinarians and diagnostic laboratories (60). When a disease is suspected or diagnosed, very rarely can a farmer make and execute a decision solely focusing on what goes on in his own farm. The farmer needs to consider how other farms in the vicinity or the external environment might be infected by a disease, and the farmer's decision about control measures needs to be consistent with statutory regulation of the disease or its treatment. Indeed, the peer effects and spatial externalities associated with a disease can amplify its transmission and spread. Rich, Winter-Nelson and Brozovic (2005) modelled the spread of foot and mouth disease (FMD) in South America and demonstrated how individual incentives to comply with disease control can be reduced if other farmers fail to enact control measures (64).

Difficult situations arise when conflicting priorities need to be resolved. Governmental agencies attempt to align legal frameworks, but in many cases incompatible considerations are at play (e.g. economic and environmental concerns). The main reason for these difficulties is that the outcomes of different actions are uncertain, which allows for political manoeuvring and public debate that can constrain the prompt control of disease and influence the choice of control measures away from those that are technically justified to those that prioritise political, environmental and economic considerations. Decisions in fish farming are contested in a public space, where political priorities and interests are strong (65). Environmental groups, interest groups and media pay close attention, and the industry is wary of negative press. This implies that, when decision processes are politicised, the industry becomes careful about revealing information, there is dispute over the evidence, policymakers try to avoid unpopular decisions, and attempts are made to do what the media and the public find appropriate. The consequence is that control decisions made by policymakers and other stakeholders might be sub-optimal with regard to the disease and the marine environment.

The rights of the individual (fish farmer) can become obstacles for public good and contribute to the 'tragedy of the commons', whereby the actions of self-interested individuals can have negative impacts on a shared resource. Rapid action is always preferable in disease control, but this can have strongly negative impacts for some groups (66). Where rights of appeal or exemptions to control measures are sought, the rights of the individual may delay action and contribute to an increased risk of disease dissemination.

As with disease control measures in terrestrial animals, in aquaculture, governments and producers often have different incentives for disease control based on different perceptions of the benefits and costs of such programmes. Free-rider problems, where individuals benefit from the actions of an intervention without paying for them, often exist in an aquaculture context (49). For example, where regulations dictate an eradication strategy, depopulation of an infected salmon farm is associated with huge costs for the individual producer while adjacent farms receive the benefits of reduced infection pressure. Indeed, individual producers may rationally decide to tolerate the disease because the marginal, or additional, costs of prevention and control are greater than the benefits. In a situation where producers are in close proximity to one another, the net effect of an environment in which producers that do not control disease interact with those that do is that it motivates all producers to decide not to implement control measures (64).

In the following sections, two case studies are used to illustrate the experiences and challenges of control of salmon disease in different settings: ISA worldwide and PD in Norway.

Case studies of infectious salmon anaemia worldwide and pancreas disease in Norway

Infectious salmon anaemia in Norway

Random mutations of the non-virulent HPR0 strain of ISAV into the virulent HPR strain are most probably responsible for the development of new index cases of ISA (67). From an index case, the virus may subsequently be dispersed horizontally by currents or other contact, causing an epidemic on a variety of spatial scales. The recent outbreaks of ISAV in the most important salmon farming regions of the world (Canada, February 2012; Norway, several in 2013; Chile, April 2013 and February 2014) demonstrate the ability of the virus to re-emerge in aquatic environments, representing a constant threat to farmed salmon and potentially to wild salmon also.

Norway experienced a serious ISA epidemic in the late 1980s and early 1990s (Fig. 3), which was controlled by depopulation and general zoosanitary measures imposed by the government and implemented in the industry. Norway has imposed the mandatory fallowing of sites (minimum two months), together with synchronised management areas (MAs) with a minimum of one month of synchronised fallowing, regardless of disease status. Recent ISA cases have been restricted to the index case or a small group of adjacent farms before being brought under control by depopulation measures, suggesting that the overall control programme is efficient (6, 68). There is no compulsory surveillance for the virus in Norway; instead, mandatory health controls are conducted by authorised fish health professionals on the basis of risk-based ISA surveillance. Farms suspected of being infected with ISA are immediately reported to the Food Safety Authorities and followed up with diagnostic verification (69). The Norwegian Food Safety Authority supervises the depopulation of infected sites and the establishment of control and surveillance zones.

Infectious salmon anaemia in Scotland

The 1998–1999 ISA epidemic in Scotland was controlled by an aggressive eradication strategy (70) that has been described as being cost-effective in moderate, bad and worst-case scenarios (33). Best practices were established to prevent or reduce the impact of future ISA outbreaks, including the establishment of MAs (71). The disease re-emerged in 2008 and 2009, but the epidemic was limited to the Shetland Islands (8). The establishment of MAs, together with limited fish movement, good husbandry and biosecurity practices, and fairly rapid depopulation of sites are reported as the main reasons for the limited impact of the 2008–2009 re-emergence (8).

Infectious salmon anaemia in Chile

In June 2007, ISA was confirmed in southern Chile and resulted in the largest single ISA epidemic on record. Since then, ISA has had a profound negative economic impact on the Chilean salmon industry, resulting in decreased revenue and job losses. At the time of the epidemic, the official authority for fish health, Sernapesca, (National Fisheries Service) and the Chilean Salmon and Trout Growers Association (private representative body, SalmonChile) established husbandry measures aimed at controlling ISA: these included early detection and depopulation (on a cage-by-cage basis), establishment of control zones, increased biosecurity, and control and treatment of waste processing. Although such measures may have helped to reduce the number of reported infected farms, the virus continued to spread and persisted throughout southern Chile for almost three years (5, 40).

In 2010, driven by the severe ISA epidemic, there was a major amendment to the General Law of Fisheries and Aquaculture, including the establishment of MAs (as in Norway and Scotland). In accordance with the OIE criteria for the establishment of compartments, the MAs were defined as places with common epidemiological, oceanographic, operational, and/or geographic characteristics (72, 73).

Chilean salmon production recovered to pre-epidemic levels in less than two years, becoming the world's second-largest producer of farmed salmon after Norway. There is concern, however, that the industry continues to experience serious infestations of sea lice and outbreaks of viral and bacterial infections, as occurred prior to the ISA epidemic (29).

Today, Sernapesca has established a targeted ISA surveillance programme (74). The most relevant aspects are the immediate notification of ISAV associated with ISA clinical signs, risk-based surveillance focusing on Atlantic salmon, stricter measures and timely control. The new programme distinguishes disease-causing variants of ISAV from those that do not produce clinical signs or mortality (HPR0), according to international scientific information and Chilean experience.

Infectious salmon anaemia in the Faroe Islands

The Faroe Islands experienced an ISA epidemic in 2000–2005 that dramatically reduced production (Fig. 2). A joint industry/governmental working group suggested reforms in industrial structure and new regulations, including the fallowing of sites, establishment of MAs, and improved hygiene in slaughter and husbandry. This culminated in the Faroese Veterinarian Act on Aquaculture (2003). The islands have not experienced an ISA outbreak since the 2000–2005 epidemic, but the non-virulent HPR0 strain is commonly diagnosed (75).

Pancreas disease in Norway

Pancreas disease of salmon was listed by the OIE in 2013. The disease is managed as an endemic disease in Scotland and Ireland, with control aimed at reducing its impact. First described in Norway in 1989 (76), PD has spread following two distinct introductions and epidemics caused by two different strains, SAV2 and SAV3 (77, 78). Neither strain has been described in wild fish, suggesting that both epidemics were largely or fully confined to farmed salmon. The disease is managed as an endemic disease in western Norway but is treated as an emergency disease from mid-Norway to the northern areas (Fig. 5). Attempts to control PD were initiated by the salmon industry, where the focus in the endemic area has been on reducing the impact of the disease. In 2006, the regional industry established the Hustadvika barrier (a 15–20 km zone with no farming activities) in mid-Norway, on the frontier between the endemic and non-endemic areas, with the purpose of preventing disease dissemination into the densely farmed areas further north in mid-Norway (Fig. 5). In 2007, the government followed this up with a regulation requiring the depopulation of infected sites in the disease-free areas (i.e. north of the barrier) and alterations to management practices (e.g. diagnostic measures, transport restrictions and MAs) in the endemic area (79). However, control of PD became a free-rider problem. Producers just north of the barrier and in close contact with the endemic zone via coastal currents (or possibly other contacts) paid the costs of control by depopulating infected sites, while farmers further north only experienced the benefits of being PD-free. The barrier has been successful in preventing further spread of SAV3, but in 2008 and 2009 it was breached by an incursion of (most likely) SAV3, with outbreaks just north of the barrier. The virus was removed by depopulating and fallowing the infected sites and disease-free status was re-established in 2010. The barrier was again breached in 2011, by strain SAV2. Despite the depopulation of several sites, SAV2 became widespread in mid-Norway. The government established a barrier against SAV2 between the counties of Sør- and Nord-Trøndelag in 2012 and a surveillance zone in the areas north of this barrier (79) (Fig. 5). Both the 2009 and 2011 PD outbreaks were preceded by others in sites just south of the barrier, causing massive infection pressure on the PD frontier. These outbreaks were not, however, followed by increased surveillance on the farms located just north of the barrier, which allowed the farms to become infected but without rapid detection.

There have been sporadic cases of PD in Northern Norway (both SAV2 and SAV3), all of which were most probably associated with the long-distance shipping of infected smolts (Fig. 5). Cases that preceded the 2007 legislation burnt themselves out and cases after 2007 have been effectively controlled by depopulation. The low density of sites in Northern Norway has probably contributed to limiting the establishment of PD in these areas.

Discussion

A number of important infectious diseases have emerged in intensive salmon aquaculture and this trend is likely to continue. Close contact with marine fauna, hydrodynamic and management links between farms, and movements of the fish are the main drivers for disease emergence. The consequences of some disease epidemics have been severe for the salmon industry and the public sector. As the salmon aquaculture sector continues to grow, the potential impacts of disease epidemics on the industry, society and environment will increase accordingly. Control of these diseases is thus essential in developing a sustainable industry.

Infectious salmon anaemia and pancreas disease: lessons learned and future perspectives

Current programmes for control of ISA in Norway, Scotland and the Faroe Islands have contributed to a reduction in the number of outbreaks and have decreased disease impacts to a manageable and sustainable level. The example cases have shown that early detection of index cases and depopulating sites using sanitary slaughter to prevent or reduce local epidemics are crucial for maintaining control of the disease. While there will always be undetected subclinical cases of ISA, such cases may burn out through the fallowing of sites, synchronised fallowing of MAs and control of effluents at slaughter. The risk of index cases initiating new epidemics will probably increase with both the size of the industry, the density of sites, and the stocking density on individual sites, all of which will require higher standards of disease surveillance and control as the industry grows.

In all three countries, the government has been the main organising body in establishing and operating the ISA control regime. At the same time, there have been important public–private partnerships in the development of the control regime (51, 71). In Chile, although the structure of the industry and surveillance and intervention are still under development, progress has been made in controlling ISA, with only one to five confirmed cases per year. In a government initiative, for example, scientific aquaculture technical committees have established expert panels aimed at providing recommendations on the evaluation of control measures to prevent the introduction of high-risk diseases or pest species and, if they occur, prevent their spread and facilitate eradication. In addition, such panels are tasked with proposing methodologies for classifying farms based on their biosecurity rankings, and with preparing proposals for the establishment of macro-areas according to the regulations, as well as evaluating health programmes in aquaculture. These Panels must include individuals from the government, industry, academia and/or independent researchers.

Pancreas disease remains an emerging threat in Norway. Its dissemination has, however, been both spatially and temporally slow, spreading gradually for more than 15 years. Although the Hustadvika barrier has prevented the spread of strain SAV3, it has not prevented SAV2 from disseminating and must be supported by surveillance and mitigation plans to maintain the current status of central and northern regions of Norway. Risk analysis and the management of identified risks are also crucial and include a common understanding of risks and commitment to mitigation measures by all the stakeholders involved. One of the challenges in operating such a barrier has been the huge cost resulting from depopulation of infected sites just north of the barrier, with such costs imposed on only a small number of salmon producers. The motivation among producers to maintain the barrier is thus highly correlated with the number of outbreaks north of the barrier, where an increase in outbreaks may lead to more political pressure to abolish the barrier. Identifying appropriate cost-sharing mechanisms is therefore crucial for the future.

While strong public–private partnerships headed by government have been a driving influence for the success of ISA control in Norway, Scotland and the Faroe Islands, such partnerships have largely been lacking in the control of PD in Norway. This may be related to differences in incentives for the government to control ISA and PD. In the late 1980s, the ISA situation in Norway interfered with the export of farmed salmon. Authorities in the United States requested that salmon carcasses from ISA-affected farms should not be certified for import, and the United Kingdom prohibited import of non-gutted salmon carcasses from Norway (51). The socio-economic implications of such a trade ban provided strong incentives for the government to control ISA and create a pilot ISA control programme. In contrast, trade restrictions have never been imposed on salmon from farms infected with PD virus. The lack of trade implications, together with the slow spread of PD, has reduced government motivation for proposing rapid control actions, and may explain why much of the responsibility for disease control has been given to the salmon industry itself. Developing strong public–private partnerships may play a crucial role in avoiding the further spread of PD in the future, particularly if PD becomes more virulent and widespread.

Institutional challenges of disease control in aquaculture

Solutions to collective-action problems, such as disease control, intrinsically rely on reliable information (80, 81, 82). Uncertainty and disagreement over knowledge make the management of common-pool resources difficult, with regard to both governmental and private initiatives. For more than 15 years, there have been debates on whether major transmission patterns of the two viral diseases, ISA and PD, are vertical or horizontal (67, 83, 84, 85). This disagreement has delayed or hindered control of these two diseases. Often, scientific studies report statistical significance but fail to quantify the causal relationships between disease properties and control measures, which are imperative for prioritising resources in a disease control operation and producing effective regulations. The more studies that are performed, the more evidence-based actions can be provided.

Public–private partnerships between government and industry associations can play a critical role in overcoming the collective-action problem, particularly where industry associations are perceived to be credible by large numbers of producers. Industry associations, however, can be less effective than public–private partnerships if they have weak leadership and thereby fail to induce members to undertake a particular course of action. At the same time, public–private partnerships need to account for the benefits and costs in the relationship (86). In terrestrial settings, the control of FMD in Brazil and recently in Colombia was accomplished through strong partnership between government and producer groups. In Brazil, the private sector has funded surveillance programmes, infrastructure costs, subsidised vaccine distribution to smaller producers and distributed vaccines to neighbouring countries where FMD is endemic (87). Developing 'carrot and stick' approaches to disease control that combine the promise of compensation for those that invest in good biosecurity measures with a schedule of fines for those that fail to report disease promptly could potentially enhance control efforts, and could be more effective than simply providing compensation alone (88).

The depth of potential public involvement varies according to context. More (2008), in the context of terrestrial animals, suggested that the responsibility for cost-sharing depends in a large part on who serves as the final beneficiary (89): in Australia, for example, where the principle of 'who benefits, pays' to determines whether the public or private sectors are more or less responsible for the costs of control. Where external impacts such as public health beyond the disease become relevant, the public sector needs to take a bigger role (89). In aquaculture, where environmental and wild fish considerations are important, this suggests a strong role for the public sector, particularly if public decisions to protect the environment affect the private profitability of the industry. However, in Norwegian and Chilean aquaculture, no compensation is paid to an individual fish farmer if disease strikes, implying that the farmer needs to bear the cost if fish are destroyed under a regulatory order. In Scotland, in contrast, there were funds available for re-establishing the industry after the 2008 ISA epidemic (90), and in Canada destruction of animals (including fish) under the Health of Animals Act may be compensated according to the market value of the animals, up to a maximum of CAD$30 per fish (91). Compensating farmers for their control efforts may also be a solution to overcome free-rider problems (49).

An additional complication in aquaculture is that the sector contains a mix of private and common resources. The Coase economic theorem states that where property rights have been allocated it is possible to find an efficient solution to an externality (such as a disease spillover) through bargaining between affected parties. In a common-pool resource, the challenge is to allocate property rights in a way that allows for both private management and control of the disease. Local self-organising that deliberately devises, monitors and enforces rules that govern their joint effort for controlling diseases can be highly effective and perceived as legitimate by those involved, but requires support by governmental agencies. The challenge may be for governmental agencies to have sufficient trust in private stakeholders to be willing to yield decision-making control. The problem of overfishing in Icelandic cod stocks in the 1970s was solved through the creation of individually transferable quotas that assigned tradable catch rights to fishers. In such a way, fishers had a greater incentive to maintain the stock, as they no longer needed to compete for the common resource (92, 93). Similarly, the development of tradable rights for public pollutants such as carbon has been implemented as a means of mitigating greenhouse gas emissions (94). Assigning tradable private-property rights to individual aquaculture producers (or industry associations) to maintain disease vigilance in the common areas in which wild stocks are present near their farms could, in a similar fashion, be conceived as an innovative means to reduce disease incidence. This is an area for future policy development to explore further.

Conclusion

Infectious diseases will continue to emerge in Atlantic salmon farming. Viral diseases such as ISA and PD have proven to be challenging to control where the action of a single producer is insufficient. Regarding ISA, control has been achieved in Norway, the Faroe Islands and Scotland, where governments have taken the main responsibility for disease management. In addition, public–private partnerships have encouraged engagement with the private sector to ensure that control options are successful. While ISA has only recently been brought under control in Chile, newly created public–private partnerships have improved the design, regulation and ruling of organised aquaculture neighbourhoods and improved biosecurity. In contrast, PD in Norway has been less systematically controlled. Technical solutions do exist, but fostering cooperation between the public and private sectors, together with development of a mechanism for cost-sharing with the private sector, would be more favourable for disease control and aid in overcoming the limitations of the current institutional system. Further work is needed to define such a structure, taking into account that the current decision-making context for both private and public sectors is marked by uncertainty, disagreements and politicised public debate, as well as too few incentives for prompt reporting of disease and a lack of effective control actions and public–private cooperation.

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Fig. 1
World production of farmed Atlantic salmon, 1980 to 2012
Source: Food and Agriculture Organization of the United Nations (3)

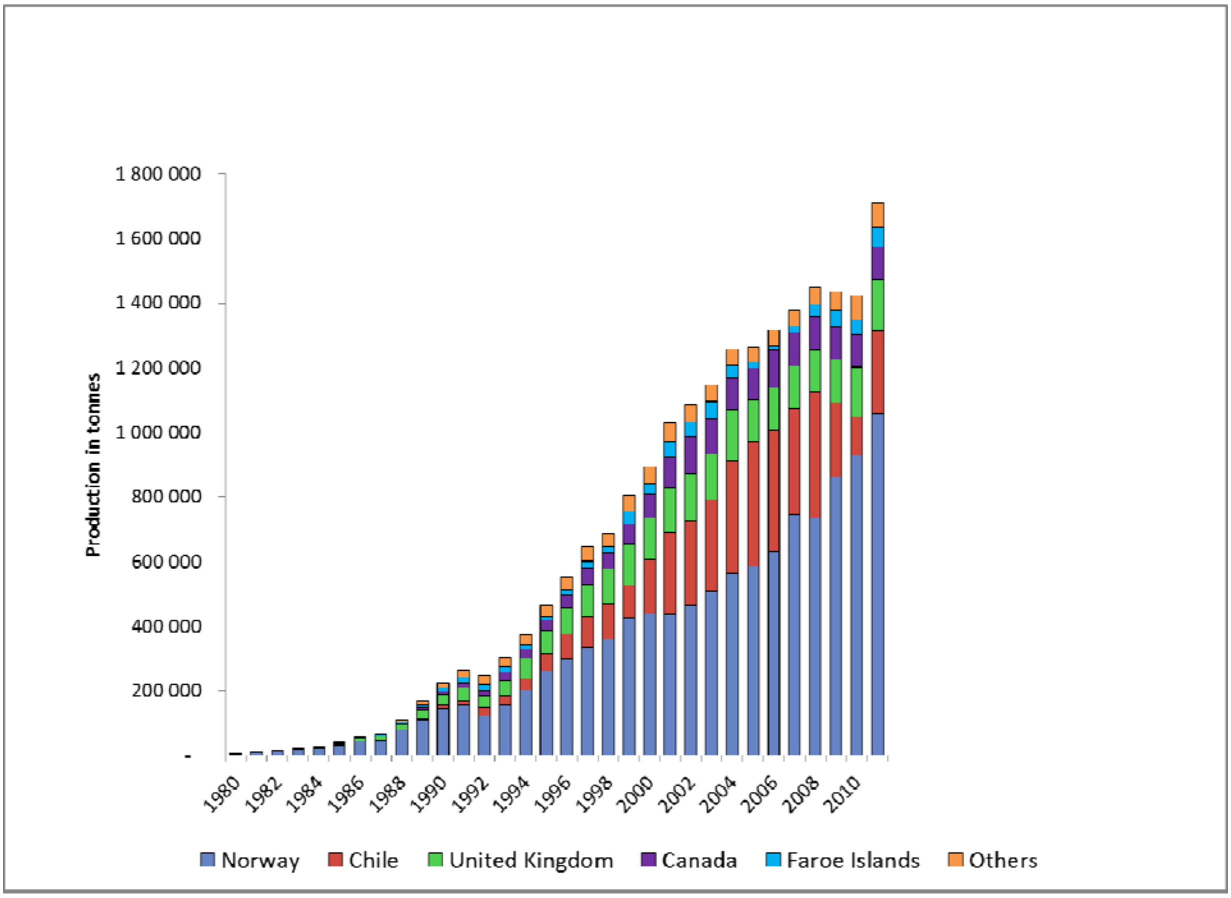

Fig. 2

Outbreaks of viral diseases in Norway, 1986 to 2012 (21)

The number of operational sites has been relatively stable during this period. The figure demonstrates the efficient control of the infectious salmon anaemia epidemic at the beginning of the 1990s. The number of infectious pancreas necrosis outbreaks has been halved during the past three years. The graph also demonstrates the emergence of diseases such pancreas disease and heart and skeletal muscle inflammation since 2000

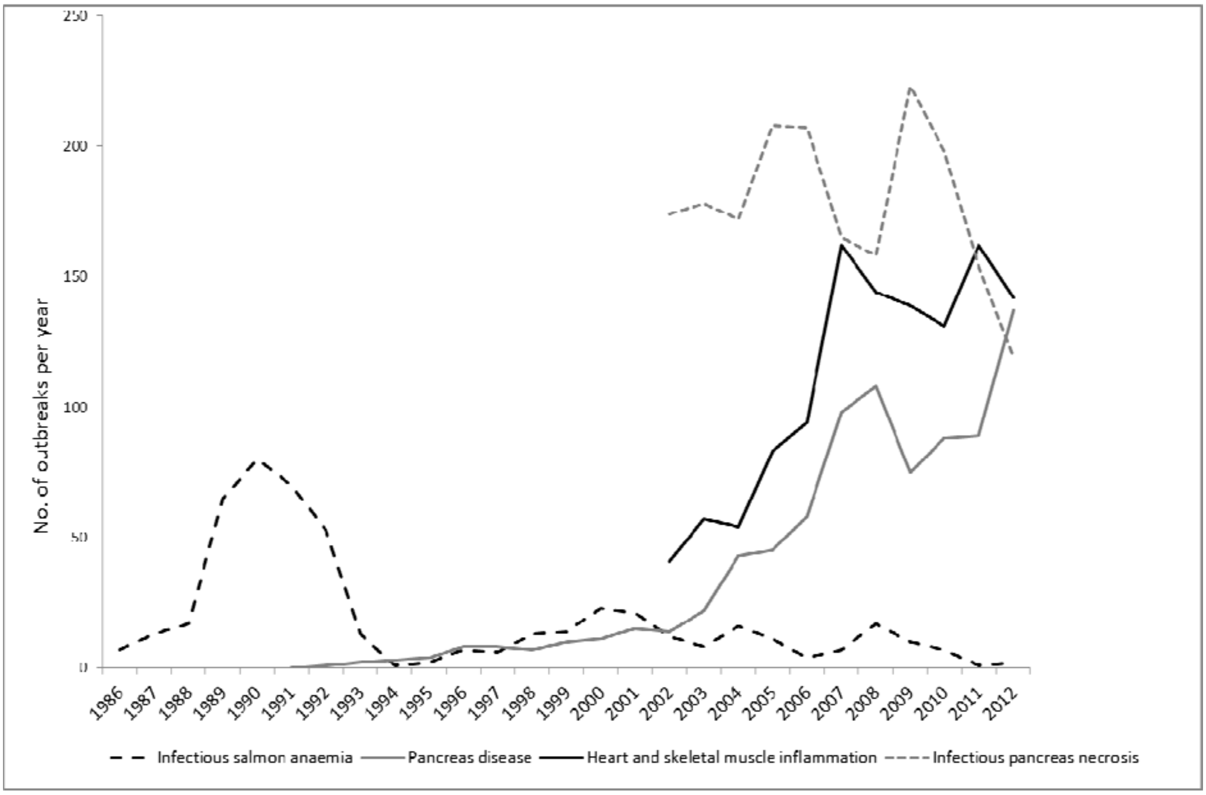

Fig. 3
Routes for the introduction of infectious diseases into salmon farms

A: Sea transfer of infected smolts
B: Well-boat traffic carrying infected fish
C: Water currents transporting disease agents
D: Wild fish, sea lice and escapees acting as disease vectors
E: Traffic of farm workers and equipment and service boats for sea-cage maintenance
F: Sea birds acting as disease vectors

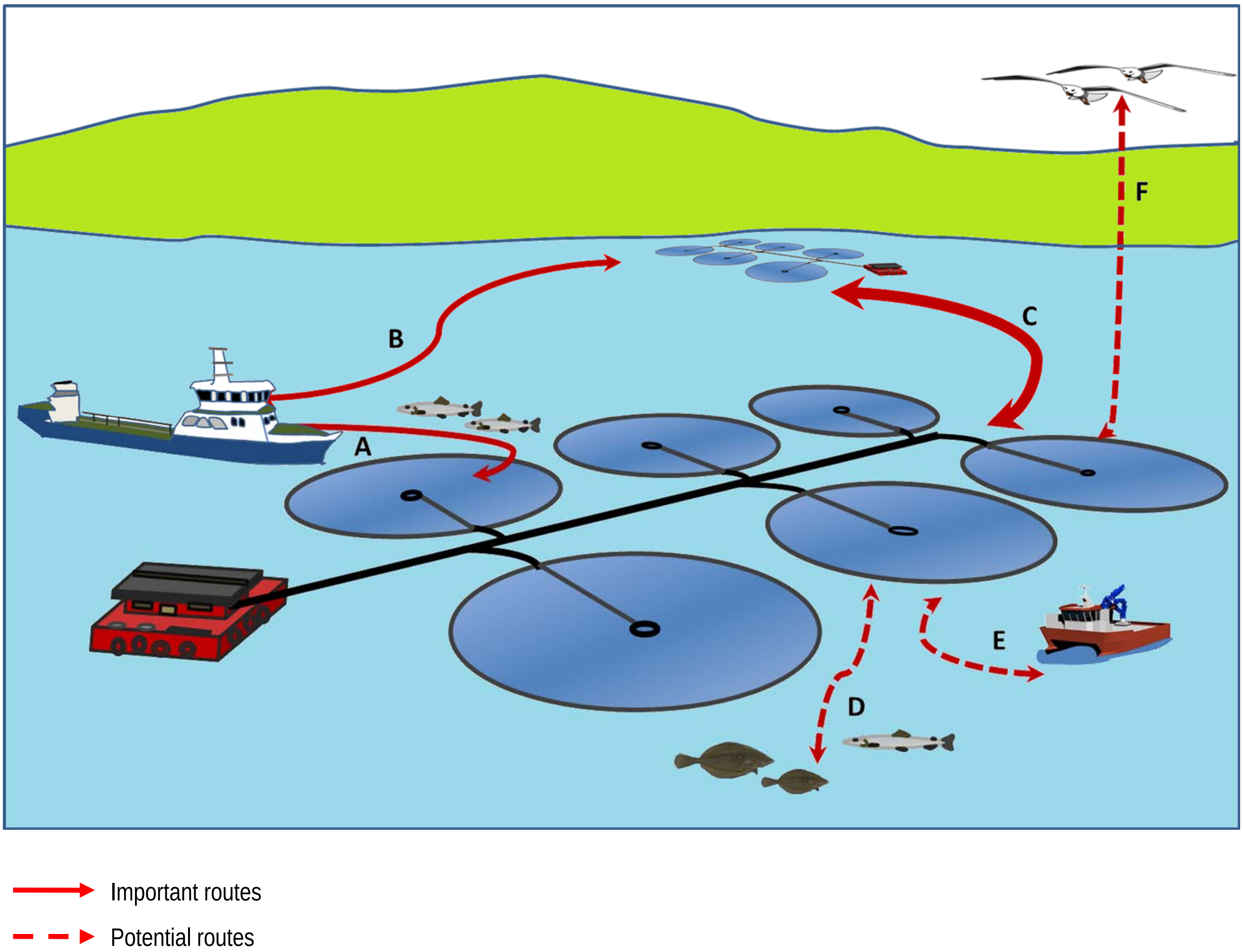

Fig. 4

Control of endemic diseases and eradication of emergency diseases

Endemic diseases are controlled by means of quantitative intervention following the law of diminishing returns. Emergency diseases are controlled by eradication of the infectious agent (46)

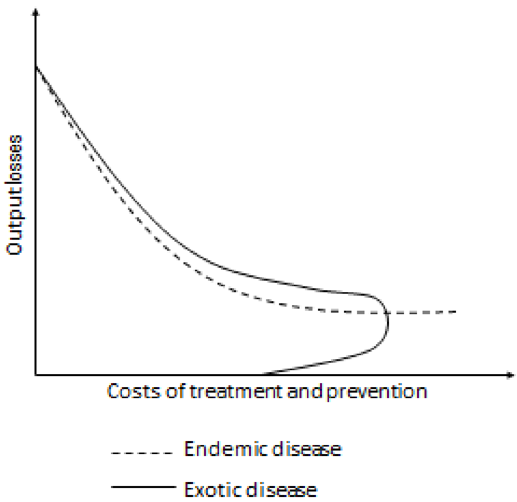

Fig. 5

Maps illustrating Norwegian salmon farms with pancreas disease

Source: Norwegian Veterinary Institute

Red dots are salmon farms recorded with pancreas disease subtype SAV-3; blue dots are salmon farms recorded with pancreas disease subtype SAV-2. The solid line indicates the 'Hustadvika' barrier. The dashed line indicates the SAV-2 barrier which was created after the new regulations in 2012